PART 5
Systems and Simulation Issues

CHAPTER 5.1
Service Requirements and Performance Criteria

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5.1 Service Requirements and Performance Criteria

This chapter describes the service oriented application of propagation models for predicting the impact of the atmosphere on the Earth-space link.

Service or system requirements and relevant criteria for a specified performance are defined and link budgets established. Practical ways to overcome propagation impairments by using fade mitigation techniques are also included. All these factors are then put together and various test cases are solved using the previously described models.

5.1.1 Generic Service Classifications

In the era of integrated service provision, no matter what the delivery medium of the service, it has become common practice to refer to a set of generic service categories. Those categories can be used to define and distinguish user services, whether or not these are delivered over satellite or cable, or in the context of fixed or mobile systems.

The importance of such a “top-down” approach to user service classification is well illustrated by the convergence of broadcast and VSAT type systems in their capability of addressing a similar subset of these services.

The classification of user services given in Table 5.1-1 was developed in the context of RACE Project 1006 in the context of broadband services.

5.1.2 System Requirements

This chapter describes a number of systems with different applications and specific sets of characteristics, and their requirements in terms of quality and availability.

5.1.2.1 VSATs

Very Small Aperture Terminals (VSATs) are designed for data transmission and distribution over a wide geographical area amongst a large number of locations. Typical examples are stock exchange information and transactions, bookmaker odds making and race data, supermarket price and stock information, company internal correspondence etc.

VSATs cannot support satellite links with large capacities, but they are cheap and easy to install and thus within the financial capabilities of small companies. They can be used to rapidly set up small capacity satellite links in a flexible way. Capacities are normally of the order of a few tens of kbit/s, but can reach up to few hundred kbit/s.

A VSAT network, usually involves a central hub station with an antenna of larger diameter (typically 4 to 11 m) and a more powerful amplifier. The hub usually houses a central host computer, which can act as a data switching centre. The architecture of the network naturally becomes star shaped, [*Maral, 1995*]. The links from the hub to the VSAT are called *outbound* links. The links from the VSAT to the hub are called *inbound* links. Both inbound and outbound links consist of two partss, uplink and downlink. It is not unusual that inbound and outbound links operate at different transmission speeds, i.e. in *asymmetrical* mode.

BASIC SERVICE		QUALITY CLASS	TYPICAL USER SERVICES
GENERIC SERVICE CLASS	**INFO. CLASS**		
DIALOGUE SERVICES	AUDIO	STANDARD or HI FI	Telephony Audioconference
	VIDEO	SUBSTANDARD or STANDARD or EXTENDED or HDTV	Video-telephony Videotelephone conference Surveillance Educational Service
	DATA (DATA)	-	Data processing Computer aided design & manufacturing Real-time control Telemetry Interactive games/amusement library Home banking Computer assisted teaching Teleworking (or Home Office) Alarm Systems
MESSAGING SERVICES	AUDIO	STANDARD or HI FI	Voice Messaging
	VIDEO	STANDARD or EXTENDED or HDTV	Business video mail (e.g. advertising spots) Personal video mail (e.g. short own made films)
	DATA (DATA)	-	Computer program downloading File transfer CAD/CAM Electronic funds transfer Teleworking (or Home Office)
	DATA (DOCUMENT)	TEXT	Teletex
		IMAGE	Telefax
		MIXED MODE STANDARD or HI QUALITY	Business electronic mail Electronic newspapers & magazines Advertising mail Teleworking (or Home Office)

Table 5.1-1: Summary service classification (continued on next page)

RETRIEVAL SERVICES	AUDIO	HI FI	Electronic record library
	VIDEO	STANDARD or EXTENDED or HDTV	Video library Home shopping Educational services
	DATA (DATA)	-	Computer program library (incl. games) Electronic directories
	DATA (DOCUMENT)	STANDARD or HI QUALITY	Electronic library (include. abstracts) Teleshopping Electronic directories (with images) Commercial telepurchases
DISTRIBUTION	AUDIO	HI FI	Radio broadcasting Corporate radio (narrowcast) Pay radio (narrowcast)
	VIDEO	STANDARD or EXTENDED or HDTV	Entertainment broadcast Education broadcast Pay TV Corporate video sessions (narrowcast) Educational/training narrowcast
	DATA (DOCUMENT)	STANDARD HIGH QUALITY	Narrowcast newspaper distribution Corporate newsletter Electronic newspaper/magazine (broadcast and narrowcast) Advertising mail Corporate newsletter (narrowcast)

Table 5.1-1(cont): Summary service classification

There are two alternatives to star shaped VSAT networks:

- One-way networks, in which the hub transmits to receive-only VSATs. This configuration supports broadcasting/dissemination services from a central site (the hub) to remote sites where the receive-only VSATs are installed.
- Two-way networks, in which VSATs can transmit and receive. Such networks support interactive traffic.

The two-way connectivity between VSATs can be achieved in two ways:

- Direct links from VSAT to VSAT via satellite, should the link performance meet the requested quality (this is the mesh network topology)
- Double hop links via satellite in a star shaped network, with a first hop from VSAT to hub and then a second hop using the hub as a relay to the destination VSAT.

Star shaped networks are imposed by power requirements resulting from the reduced size and hence the low cost of the VSAT earth station in conjunction with power limitation of the satellite. Meshed networks are considered whenever such limitations do not hold, or are unacceptable. Meshed networks have the advantage of a reduced propagation delay (single hop delay is about 0.25 s, whereas a double hop would take on average 0.5 s). Smaller delay is of particular interest for telephony and/or conferencing applications.

One-way VSAT networks support the following types of services:

- Stock market and other news broadcasting

- Updates of market related data, news and catalogue prices
- Distribution of video or TV programmes
- Distribution of music in stores and public areas
- Relaying of advertising to electronic signs in retail stores

Two-way networks support:

- Interactive computer transactions
- Low rate video conferencing; satellite news gathering (SNG)
- Database enquiries, E-mail
- Bank transactions, automatic teller machines
- Reservation systems; sales monitoring and stock control
- Distributed remote process control and telemetry; medical data transfer
- Voice communications
- Emergency services

Most of the two-way services deal with interactive data traffic, where the user terminals are most often personal computers. The most notable exceptions are voice communications and SNG.

Depending on the service the traffic flow between the hub and the VSATs may have different characteristics and requirements:

Data transfer or broadcasting which belongs to the category of one-way services, typically displays file transfers of 1 to 100 MBytes of data. This kind of service is not delay sensitive, but requires a high integrity of the data which are transferred.

Interactive data is a two-way service corresponding to several transactions per minute and per terminal of single packets 50 to 250 Bytes long on both inbound and outbound links. The required response times are typically a few seconds.

Enquiry/response is a two-way service corresponding to several transactions per minute and terminal. Inbound packets (typically 30 to 100 Bytes) are shorter than outbound packets (typically 500 to 2000 Bytes). The required response time is typically a few seconds.

Supervisory control and data acquisition (SCADA) is a two-way service corresponding to one transaction per second or minute per terminal. Inbound packets (typically 100 Bytes) are longer than outbound packets (typically 10 Bytes). The required response time ranges from a few seconds to a few minutes. What is most important is the high data security level, and the low power consumption of the terminal.

Each communication service demands certain features of its delivery system in terms of:

- connectivity
- connection delay
- transmission delay
- link quality
- transmission capacity

The degree of connectivity determines whether the service is private, semi-private or public. Connection delay depends on the service. For example, a voice connection could be allowed a longer call set up delay than say a datagram service. Excessive transmission delay can affect a real-quality may not be so critical for a real time service with a high redundancy alphabet (speech) but is more critical for a funds transfer service. Transmission capacity is a function of the source information encoding process and the efficiency in being able to decode at the sink. Transmission capacity requirements are also dependent on the cost of the transmission media.

Response time is defined as the time elapsed between emission of speech and reception of the other talker's response in case of voice telephony communications, or time elapsed between transmission of an enquiry message initiated on a transmitting computer and the appearance of the first character of the response message on the receiving computer screen.

Response time for data transfer builds up from several components:

- queuing time at the transmitting side as a result of possible delay for capacity reservation before transmission occurs;
- time for transmission of the emitted message which depends on the length of the message and the transmission bit rate;
- propagation time which occurs on the forward and return links;
- processing time of the enquiry message at the receiver, and time necessary for generating and transmitting the response;
- protocol induced delay, as a result of error recovery and flow control between the transmitting and receiving sides.

The VSAT network is only responsible for the routing delay which includes propagation delay and processing delay as a result of protocol handshake between VSATs and hub front end processor, but excludes the processing delay of the data terminal equipment.

A VSAT network user is only concerned by the baseband link quality, which is stipulated either in signal power to noise power ratio, S/N, for analogue signals, or in Bit Error Rate (BER) for digital signals.

For analogue television, a typical S/N objective is 50 dB. This ensures recovery of a signal with a quality suitable for subsequent terrestrial broadcasting or cable distribution. For digital transmission, a typical BER objective is 10^{-7}. This objective guarantees an acceptable quality for voice or video communications. For data communications, the bit error rate is not a significant parameter, as the transmission can be made error-free due to the retransmission protocols that are usually implemented between end-to-end terminals. However, the bit error rate influences the number of required retransmissions, hence influences the delay.

In general terms, availability is defined as the ratio of the time a unit is functioning , to the total time of usage. Network link availability is the percentage of time the service is delivered at a given site with the requested quality (BER less than specified value; response time within specified limits). Network availability builds upon equipment reliability, propagation impairments, and Sun transit outage.

More precisely, network availability can be expressed as $A_{net} = A_{Tx}A_{sat}A_{link}A_{Rx}$ where A_{Tx} is the transmitting earth station availability, A_{sat} the space segment availability, A_{link} the link availability, and A_{Rx} the receiving station availability. Table 5.1-2 gives some typical equipment availability figures.

Equipment	Remote VSAT	Space Segment	Link	Hub	Network
Availability [%]	99.9	99.95	99.9	99.999	99.7

Table 5.1-2: Typical figures for availability, [*Maral, 1995*]

An availability of 99.7 % corresponds to a cumulative down time of 26 hours per year. However, it

Should the service interruption be caused by equipment failure, an appropriate maintenance procedure should be implemented to restore the service within the requested time. This is particularly crucial for the hub station, as its outage affects the whole star network. Should propagation impairments be responsible for the service interruption, then site diversity can be considered. Finally, back-up terrestrial connection may be a means to achieve service continuity.

5.1.2.2 DVB-based Multimedia System at the Ku-Band

In the following, a system description and performance quality are given for a DVB (Digital Video Broadcasting) based system operating at Ku-band to provide PC-based Internet and data broadcasting services via satellite.

The traffic for multimedia applications on the Internet is mainly asymmetric: almost all browsing traffic involves much more data moving from the server to the end-user than in the opposite direction, especially for video or audio applications. This system is thus asymmetric and takes advantage of TV broadcasting techniques for the forward link; the return link may use a telephone line/modem.

There are two components to this system; the uplink site, where the base station operates as a DVB broadcaster and as a satellite gateway operator and the downlink site, where the end-users PCs receive the Internet and data broadcaster services.

The base station consists of a DVB uplink and a satellite router/server, which are directly interconnected with a DVB gateway. It performs basic server tasks and delivers IP datagrams encapsulated in an MPEG-2 data structure. The DVB uplink performs all necessary multiplexing, coding and modulation tasks for transmitting data over a direct broadcast satellite, at a data rate up to 40 Mbit/s.

The user equipment consists of a small satellite dish (whose size depends on the location of the downlink site, for instance 60 cm over western Europe) and a DVB PC-board for processing the incoming satellite data. A standard World Wide Web (WWW) browser with any necessary plug-ins is used for interaction with the system.

The DVB PC board performs demodulation, decoding and demultiplexing, reconstructs IP datagrams from the cells and routes internally to the appropriate applications. The end-user stations can access the base station in a number of ways, for instance a telephone line/modem.

Satellite Internet access can support the following applications:

- High-speed Internet access: data are requested via the return link and retrieved over the satellite link at, for example, 2 Mbit/s
- On-demand services: transmission of the request on the return link and data are retrieved over the satellite link
- Data broadcasting: data are filtered by the multicast or broadcast services from the local hard disk and no return link is therefore required
- Intranet/Extranet: data are requested via the return link and retrieved over the satellite link, or data are pushed to the end-user PC.

Since the system uses DVB, it ensures “Quasi Error Free” (QEF) operation with approximately one uncorrected error event per transmission hour; the corresponding BER ranges between 10^{-10} and 10^{-11} at the input of the MPEG-2 multiplexer. The nominal availability of the system is 99.7% of the year.

5.1.2.3 Multimedia GSO/NGSO Configurations

In addition to the VSAT system and the DVB Multimedia requirement presented before, a few other types of multimedia consumer networks are considered here. These kinds of systems will benefit from propagation prediction methods which take the specific choice of frequencies and operational parameters into consideration. The technical background for the systems in question is similar to that for VSATs, but one major difference could be that these small multimedia earth stations for the consumer are planned to be sold like GSM hand-held terminals, not needing an individual transmission licence.

This is a star-type network with both incoming and outgoing traffic. In the outgoing direction (from the hub to the consumer), the normal Ku-band Direct-To-Home bands are used: 12.75-13.25 GHz, 13.75-14.50 GHz, and 17.30-18.10 GHz for the uplink and 10.70-12.75 GHz for the downlink.

In the return direction, from the consumer to the hub, a 80 or 120 MHz channel at Ka-band is used with 29.50-30.00 GHz for the uplink and 18.30-18.80 GHz for the downlink to the hub.

The services envisaged for the system include:

- General data gathering for e.g. enterprises with many branch offices, affiliates, business associations or employees working at home, including store & forward and transfer of traffic into terrestrial infrastructure
- Feederlink for data content, including real time (High-Speed Internet and IP Multicast) and non-real time (file transfer) applications
- Live interactions (e.g. requests, votes, still images and low quality video, video conferences) for remote learning/training applications.

The forward path of the digital system is based on MPEG transmissions, using relevant ETSI, DVB and DAVIC standards, and also the return path uses digital standards, so that Internet Protocol and Asynchronous Transfer Mode (ATM) can be used on the network. The range of applications that need to be supported require a flexible standard, ensuring QEF transmission (equivalent to a bit error rate on the satellite link not exceeding 10^{-10}, while the link is considered available).

The hub station will use an antenna with a diameter of 6 to 9 m, possibly with site diversity. The consumer Satellite Interactive Terminal (SIT) consists of an Outdoor Unit (ODU) with an antenna diameter of 0.6-1.2 m. The SIT also contains an Indoor Unit (IDU), functioning like a modem, attached to a User Device, which can be a PC or a TV set.

Maximum transmission power at around 29.7 GHz will be 0.5 W for the small 60 cm antenna, and 2 W with the 1.2 m antenna. The polarisation is linear, with polarisation re-use in a total of 8 uplink beams covering Western and Central Europe on the first satellite (ASTRA-1H). A 'receive before transmit' procedure will be inherent in the SIT. The maximum user data rate will be 144 kbit/s to 2 Mbit/s.

The BER on the satellite link should not exceed 10^{-10} for it to be considered available. The design guideline for the return link availability is better than 99.5 % of an average year.

5.1.2.4 Future Geostationary Ka/Ka-Band Consumer Systems

While the system described above is already being built, future systems operating exclusively at 20/30 GHz are under consideration by many operators. The most likely bands for GSO Ka-band consumer systems are 27.5–28.6 GHz and 29.1–30.0 GHz for the Uplink and 18.3–18.8 GHz, 19.3-20.2 GHz and 21.4–22.0 GHz for the downlink.

In these bands, one-way star-type networks from hub to consumer are likely to appear, but also two-way systems. These may either be via the hub in both directions, but could also be for direct

It is most likely that due to propagation factors, these Ka-band networks will not be based on high reliability, and therefore reliable propagation predictions valid for time percentages around 99.0 to 99.9 % of a year would serve this purpose.

5.1.2.5 Particular Considerations for Non-Geostationary Systems

Non-Geostationary (NGSO) networks are now being planned with consumer terminals in the range 10.7–30.0 GHz. Users will not only be mobile, but more typically with antennas mounted on or near houses. A constant link with a satellite in a NGSO constellation is maintained by the antenna, which follows the moving satellite and typically every few minutes switches to another satellite. This raises a particular question on fade dynamics in NGSO systems, when disregarding the mobile use. The fade dynamics in such NGSO systems will not be determined by the movement of the rain cell relative to the Earth, but rather by the beam movement across the rain cell, when following a satellite. A model for fade duration/interval or fade slope under these circumstances would be of particular interest.

Also the normal use of elevation angles near 90° will be new in Europe, and it may necessitate modifications to the existing ITU-R propagation model, which is based on static conditions and elevation angles in Europe typically below 40°.

5.1.3 Performance Objectives and Evaluation

For radio-relay system planners it is of vital importance to have outage prediction methods at hand in order to optimise each hop, technically and economically, according to a requested transmission quality. According to ITU-T, each direction of a path can be in one of two states, available time or unavailable time. Error and availability performance objectives are specified and measured for available time. A bi-directional path is in the unavailable state if either or both directions are in the unavailable state.

Error performance objectives of an international digital connection operating **at a bit rate below the primary rate** 2.048 (1.544) Mbit/s and forming part of an ISDN, are given in ITU-T Rec. G.821.

The error performance objectives in this recommendation are stated for each direction of a N x 64 kbit/s connection ($1 \leq N < 32$ (24)) independent of the transmission medium. Prior to the approval of ITU-T Rec. G.826, real digital radio-relay links forming part of the high-, medium- and local grade portion within an ISDN were designed by applying the error performance objectives for connections at a bit rate below the primary rate, directly at the system bit rate. Translation rules have been used to normalise error performance measurements obtained at the system bit rate to the 64 kbit/s level.

The following error performance events are defined:

- Errored Second (ES): a one second period in which one or more bits are in error
- Severely Errored Second (SES): a one-second period which has a bit-error ratio> 10^{-3}.

The following error performance parameters are defined:

- Errored Second Ratio (ESR): the ratio of ES to total seconds in available time during a fixed measurement interval
- Severely Errored Second Ratio (SESR): the ratio of SES to total seconds in available time during a fixed measurement interval.

Error performance parameters and objectives for international, constant bit-rate digital paths **at or above the primary rate** 2.048 (1.544) Mbit/s, are given in Rec. G.826. The recommendation is reference path (HRP). It applies as well for PDH, SDH and ATM-network. It is also independent of the transmission medium. One big difference between G.821 and G.826 is that in G.826 the parameters are based on errored blocks and not on errored bits. A block is a set of consecutive bits associated with the path.

The parameters defined in G.826 are based on the following events:

- Errored Block (EB): a block in which one or more bits are in error
- Errored Second (ES): a one second period with one or more errored blocks
- Severely Errored Second (SES): a one-second period, which contains 30 % errored blocks or at least one defect. SES is a subset of ES
- Background Block Error (BBE): an errored block not occurring as part of an SES.

The following error performance parameters are defined:

- Errored Second Ratio (ESR): the ratio of ES to total seconds in available time during a fixed measurement interval
- Severely Errored Second Ratio (SESR): the ratio of SES to total seconds in available time during a fixed measurement interval
- Background Block Error Ratio (BBER): the ratio of BBE to total blocks in available time during a fixed measurement interval. The count of total blocks excludes all blocks during SESs.

The path fails to meet the error performance requirements if any of the objectives is not met.

The end-to-end objectives are divided into one national portion and one international portion. For terrestrial systems, the *national portion* is subdivided into three basic sections: Long haul-, Short haul- and Access network sections. The *Long haul section* shall make use of the distance based allocation and part of the fixed block allocation. The *Short haul section* shall make use only of the fixed block allocation contribution. The *Access section* shall make use only of the fixed block allocation contribution.

Availability parameters and objectives for path elements of international constant bit-rate digital paths at or above the primary rate are given in ITU-T Rec. G.827. The recommendation is applicable to digital paths based on PDH, SDH and some other cell-based (ATM) transport networks.

Performance objectives are given for two availability performance parameters, availability ratio and mean time between digital path outage:

- Availability ratio (AR): the ratio of time that a path element is in the available state to total time during an observation period. The converse of AR, the unavailability ratio, UR, is defined as UR = 1 - AR
- Mean time between digital path outages (Mo): the average duration of any continuous interval during which the digital path portion is available.

In the fixed-satellite service availability objectives are given in ITU-R Rec. S.579 for a satellite HRDP used for telephony and using pulse-code modulation (PCM) or as part of an ISDN hypothetical reference connection. This Recommendation specifies unavailability due to both equipment and propagation. Unavailability due to equipment should be not more than 0.2 % of a year. Unavailability due to propagation should be not more than 0.2 % of any month, which corresponds to 0.04 % of any year with a conversion factor of 5.

Prior to the approval of ITU-T Rec. G.826 and ITU-R Recommendations. F.1189 and F.1092, real digital radio-relay links forming part of an ISDN were designed by applying the error performance objectives of G.821 and related ITU-R Recs. directly at the system bit rate. As a consequence, system bit rate to 64 kbit/s level and all outage predictions were made for a BER equal to 10^{-3} which defines a SES event in G.821.

5.1.4 Quality and Availability in Mobile Satellite Systems

Operators of mobile satellite systems need to calculate power link budget margins to guarantee a certain degree of coverage. In these systems power is a valuable resource, and the link margin should be as small as possible while still obtaining the required availability. Practical experience indicates that the traditional method of calculating the link margins directly from the channel cumulative density functions is a too pessimistic approach, the link budgets contain unnecessary power margins. Another problem often encountered results from applying availability and quality time requirements as defined for terrestrial cable systems, to mobile satellite systems, as addressed in ITU-R Question 112/8.

The traditional method of calculating fade margins has been to use the channel fade depth at a given percentage of distance or time. There are other approaches where the benchmark is the system performance, e.g. in our case the bit error rate, and not solely the channel fluctuations due to multipath.

The average bit error rate method to calculate the necessary fade margin results in decreased fade margin compared to the traditional method. The key point is to note the different parameters used, that is purely fade statistics or average bit error rate. An additional quality parameter, which could be applied, is the instantaneous bit error rate. This approach turns out to be exactly the same as the traditional method of fade margin calculations based purely on the channel statistics when the availability required is A=100%. The two approaches can be merged into a combined method taking into account both average and instantaneous bit error probability when the system is available.

The instantaneous bit error rate shall typically exceed 10^{-3} during less than I % of the time (for instance I = 99%) during the time when the average bit error rate requirement is fulfilled. The percentage I depends on the application's sensitivity to error bursts and could be a quality of service parameter negotiated at connection set-up between the application and the network.

Calculating the needed fade margin to satisfy the instantaneous bit error probability leads to an increased fade margin compared to the average method in some cases.

The combined method utilises the short term or instantaneous availability method given that we are in a period of long term availability in a combined approach to satisfy both requirements. It is an additional requirement, which increases the quality with respect to the instantaneous bit error rate during the time A in which the long term bit error rate requirement is met.

The overall fade margin MC is the larger of the two margins MA and MC; the margin MA is related to the average bit error probability within the availability region A.

Both the average method and the combined approach result in smaller fade margins than the traditional method based on channel power statistics. Although the actual system availability and quality decrease with decreasing fade margin, the target availability and quality is still met with reduced power margin.

The combined approach, targeting both the average and the instantaneous bit error probability in the available region, separates the terms availability and quality. The method gives fade margins in the range mobile satellite operators employ, which are based on experimental results. The method results in lower calculated fade margins than compared to the traditional approach where channel cumulative distribution functions are used.

Further work could include using the packet or frame error rate instead of the bit error rate as in of interest that could be considered. Establishment of a method between time based availability and quality criteria and statistical approaches could be further elaborated.

5.1.5 Systems Architectures and Communications Technologies

5.1.5.1 Systems Convergence

In the past we have been used to having individual communications services provided by physically discrete networks. We are currently moving to integrated service provision over physical networks that are transparent to the user. The user services supported on such networks are then perhaps best classified in a general way (see Table 5.1-1).

Examples of this convergence are to be found in our test cases. We note in particular the use of direct broadcast links with a return path and, although the traffic on such systems is highly asymmetric, there is an obvious convergence with conventional VSAT systems. Also to be noted is the use of LEO systems for multimedia services to both fixed and mobile terminals.

5.1.5.2 Frequency Bands

Relevant frequency bands for current and next generation satellite systems are listed in Table 5.1-3. It is to be noted that most of these are allocated for shared use with terrestrial systems. Also to be noted is the imminent use of the 47/48 GHz bands by High Altitude Platforms (HAPs), which are classified by the ITU as being terrestrial systems.

5.1.5.3 Orbits, Radio Paths and Terminals

There are several kinds of satellite links and orbits. These and their combinations affect the propagation characteristics of radio paths and dictate the capabilities of earth station terminals. In the broadest sense, Earth terminal to satellite links can be classified as fixed (point-to-point, point-to-multipoint, broadcast) or mobile (hand held or vehicular based terminals, including personal communications). Links between satellites (intersatellite links) facilitate complex but efficient ways of deploying large communication network systems.

The geostationary earth orbit (GEO) is in the equatorial plane at an altitude of 36,000 km with a period of one sidereal day (23 h 56 m 4.09 s). GEO satellites appear to be almost stationary from the ground (subject to small perturbation) and the ground antennas pointing to these satellites may need only limited or no tracking capability. The radio paths between ground terminals and a satellite are at a fixed angle (elevation and azimuth).

A GEO satellite cannot "see" the Earth above 81.3º latitude. A geosynchronous orbit has a period, which is a multiple of the Earth's rotation period, but it is not necessarily circular and it may be inclined. Therefore, GEO is a special case of a geosynchronous orbit. Molniya and Tundra orbits are critically inclined (inclination angle of 63.4º) elliptical orbits (HIEO) to cause the satellite's subsatellite ground trace to dwell at apogee at the same place each day. Such orbits whose subsatellite paths trace a repetitive loop allow several satellites to be phased to offer quasi-stationary satellite service at high latitudes.

The orbits for which the highest altitude (apogee) is at or greater than GEO are sometimes referred to as high Earth orbits (HEO). Low earth orbits (LEO) typically range from a few hundred kilometres to about 1000 km and medium Earth orbits (MEO) are at intermediate altitudes. Any non-geostationary orbit will normally result in a variable angle radio path, regardless of whether the earth station terminal is fixed or mobile. This imposes an antenna tracking requirement upon the terminal.

FREQUENCY BAND	FREQUENCY	SERVICE/ EXAMPLE SYSTEM
L-Band	1.6/1.5 GHz	Mobile/INMARSAT, IRIDIUM
S-Band	~ 2 to 2.4 GHz	Mobile/ICO Global
C-Band	6/4 GHz	PSTN, Video and VSAT/ INTELSAT, ANIK, US Domestic, PALAPA
X-Band	8/7 GHz	Military VSAT/Skynet
Ku-Band	14/11 and 14/12 GHz 17/12 GHz	PSTN, Video/ INTELSAT, EUTELSAT DBS/ASTRA
Ka-Band	30/20 GHz 44/20 GHz	Multi-Media/TELEDESIC Military VSAT/ MILSTAR, Skynet IV
V-Band	48/47 GHz 40/50 GHz	Multi-Media/Skystation (HAP)

Table 5.1-3: Some relevant frequency allocations

Full earth coverage from a constellation of LEO satellites is possible with circular polar constellations and constellations of orbit places with different inclinations. Intersatellite links among the differently inclined orbit planes are difficult.

5.1.5.4 Payload Technology

The traditional function of a communications satellite is that of "bent pipe" quasi-linear repeater in space. Uplink signals from ground terminals directed at the satellite are received by an antenna onboard the spacecraft. They are then amplified, translated to a different downlink frequency band, channelised into transponder channels, further amplified to a relatively high power, and retransmitted towards the earth. Transponder channels are generally rather broad (e.g. bandwidth of 36 MHz) and each may contain many individual or user channels.

Satellite operators can use available transponder channels and multiple antenna beams (including steerable antennas and spot beams) to facilitate basic switching of signals, optimum frequency re-use and minimise interference between both satellite and terrestrial systems.

Newer satellite architectures may use regenerative repeaters which process the uplink signals by demodulating them to baseband. These baseband signals, which may be for individual users or may represent frequency division multiplexed (FDM) or time division multiplexed (TDM) signals from many users, are routed to downlink channels, modulated onto one or more radio frequency carriers and transmitted to the Earth.

5.1.5.5 Transponder Utilisation, Access and Modulation

Satellites act as central relay nodes, which are visible to a large number of users who must use the limited power and bandwidth resources efficiently. Multiple access techniques allow many users to share a satellite's resources of bandwidth and power and to avoid interfering with each other and with other satellite or terrestrial systems. Multiple access schemes segregate users by frequency, space, time, polarisation, and signalling code orthogonality. The test cases considered within COST 255 have mainly not considered issues of transponder utilisation and/or associated interference.

Frequency Division Multiple Access (FDMA) has been the most prevalent access for satellite systems until recently. Individual users assigned a particular frequency band may communicate at any time. Satellite filters subdivide a broad frequency band into a number of transponder channels.

operated in a backed off condition which results in the reduction (output back off) of the output power of the individual carriers. For amplifiers with many carriers, the intermodulation products have a noise-like spectrum and the noise power ratio is a good measure of multicarrier performance.

Time Division Multiple Access (TDMA) users share a common (wide) frequency band and are each assigned a unique (short) time slot for their digital transmission. At any instant there is only one carrier in the transmit amplifier, requiring little or no backoff from saturation. A drawback is the system complexity required to synchronise widely dispersed users in order to avoid intersymbol interference caused by more than one user signal appearing in a given time slot. The total transmission rate in a TDMA satellite channel must be essentially the sum of the users' rates, including overhead bits, such as for framing, synchronisation and clock recovery, and source coding.

Code Division Multiple Access (CDMA) modulates each carrier with a unique pseudo random code, usually by means of either a direct sequence or frequency hopping spread spectrum modulation. As the CDMA users occupy the same frequency band at the same time, the aggregate signal in the satellite amplifier is noise-like. Individual signals are extracted at the receiver by correlation processes. CDMA tolerates noise-like interference but does not tolerate large deviations from average loading conditions. One or more very strong carriers could violate the noise-like interference condition and generate strong intermodulation signals.

User access is via assignments of a frequency, time slot, or code. Fixed assigned channels allow a user unlimited access. However, this may result in poor utilisation efficiency for the satellite resources and may imply higher user costs (analogous to a leased terrestrial line). Other assignment schemes include demand assigned multiple access (DAMA) and random access (e.g. for the Aloha concept). DAMA systems require the user to first send a channel request over a common control channel. The network controller (at another earth station) seeks an empty channel and instructs the sending and receiving units to tune to it (either in frequency or time slot). A link is maintained for the call duration and then released to the system for other users to request. Random access is economical for lightly used burst traffic such as data. It relies on random time of arrival of data packets and protocols are in place for repeat requests in the event of collisions.

In practice, combinations of multiplexing and access techniques may be used. A broad band may be channelised or frequency division multiplexed (FDM) and FDMA may be used in each subband, e.g. FDM/FDMA. Other combinations are also used.

Efficient source encoding algorithms, coupled with forward error correction channel coding have brought about the dominance of digital modulation methods such as M-ary PSK and QAM in virtually all contemporary satellite communications services. Quality of a digital link can be specified, controlled and guaranteed on an end-to-end basis.

5.1.5.6 Rationale for Test Cases

Test cases were chosen in accordance with the following broad objectives:

- to illustrate how the propagation factors can be applied in system design
- to apply the latest propagation data both to the performance prediction of existing systems (for example existing VSAT and DBS systems) and to future systems
- to cover the range of frequencies for which the COST 255 project has contributed substantial relevant propagation data and models
- to cover a representative range of systems applications especially including multimedia techniques.

The systems architectures taken for the test cases were either those of existing systems (for example leap in technology. It was not seen as the role of the test cases to study novel system architectures or to apply a detailed analysis to unproven technologies. Advanced technologies have thus been avoided and though it was recognised that on-board processing (including regeneration) would lead to significant system performance improvements, especially for Ka and V band systems, bent-pipe transponders have been taken in all test cases.

As a minimum it was expected that detailed link budgets and coverage evaluations would be undertaken for each test case. For the fixed link applications, reference stations were identified in the coverage regions for which time-series data were available for evaluating fade mitigation techniques through simulations. These reference stations were also those used for calculating detailed link budgets.

It was taken to be essential to cover both fixed and mobile systems and to examine the types of orbits currently being used, including LEO examples in addition to GEO systems. The test cases finally chosen are listed in Table 5.1-4.

Test Case	Fixed or Mobile	Orbit	System Description
1	Fixed	GEO	Ku-Band VSAT System
2	Fixed	GEO	Ka-Band VSAT Videoconference System
3	Fixed	GEO	V-Band Asymmetric Multimedia System
4	Fixed	LEO	Ka-Band Iridium Feeder Link
5	Mobile	LEO	L-Band Low-Bit Rate System
6	Mobile	LEO	Ka-Band Multimedia System

Table 5.1-4:Test case studies

5.1.6 References

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CHAPTER 5.2
Propagation Impairments and Impact on System Design

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5.2 Propagation Impairments and Impact on System Design

In this chapter, both the propagation effects and the system design are considered by investigating the impact of propagation impairments on the design of future satellite systems. Based on investigations of propagation effects, evaluation concepts are developed which are suitable for proper system design. Thus, a means is produced to map propagation effects into system parameters, such as the required link margin or the required dynamic range for fade mitigation techniques.

The evaluation concepts developed in this chapter are valid for and applicable to all kinds of services – fixed, portable, and mobile. The evaluation results, however, focus on fixed and portable services, since the propagation measurements have been performed using the 40 GHz beacon of the geostationary satellite ITALSAT and a non-mobile – fixed or portable – station on the ground.

5.2.1 Propagation Impairments

The propagation effects are investigated using beacon measurements. Therefore, the combined effects of gaseous, cloud, rain and ice attenuation are considered and the evaluation of the measurement results focuses on the net effect on the communication link. Moreover, the propagation phase noise is investigated. Especially, the impact of propagation phase on the system design for portable terminals is considered. Other propagation effects, such as scintillation or rain and ice depolarisation are not taken into account.

5.2.2 Impact of Atmospheric Attenuation on System Design

The design of SATCOM systems has to satisfy several requirements. Among others the link availability is an important issue, which strongly influences the required fade margin. Appropriate figures for the fade margin can be derived from the cumulative distribution of attenuation that gives the percentage of time for which a certain attenuation level is exceeded. Various versions of these distributions exist, reflecting seasonal and diurnal variations. It depends on the requirements of the supported service, which of these versions has to be taken into account. To illustrate this issue, consider three imaginary services denoted *A*, *B*, and *C*, all of them requiring the same link availability. We assume that the required link availability for service *A* has to be satisfied on average over the whole year, whereas services *B* and *C* require the link availability to be guaranteed for every month and for the evening hours, respectively. Obviously, the different requirements of these services yield different fade margins, since signal attenuation is subjected to both seasonal and diurnal variations. As a result, service *C* requires the largest link margin, whereas considerably smaller link margins suffice to satisfy the link availability requirements for services *A* and *B,* with the smallest link margin for service *A*.

In addition to link availability other parameters may be of interest in applications such as TV and audio broadcasting. A link availability of 99.9 % only indicates that a loss of service occurs on average during 8:45 hours a year. However, this figure does not reveal for how long and how often the service is expected to be interrupted: the link could be interrupted a thousand times a year for about 30 seconds or about 50 times a year for 10 consecutive minutes. A service provider offering payTV may see a big difference between these two situations. Rather than in link availability a service provider may be interested in outage probability [*Fiebig and Schnell, 1997, 1998*] which is the probability that a specific attenuation level is exceeded for more than τ consecutive minutes during a specific time interval which corresponds with the length of a film or sporting event. Thus, fade margin design can also be carried out with respect to a tolerable outage probability.

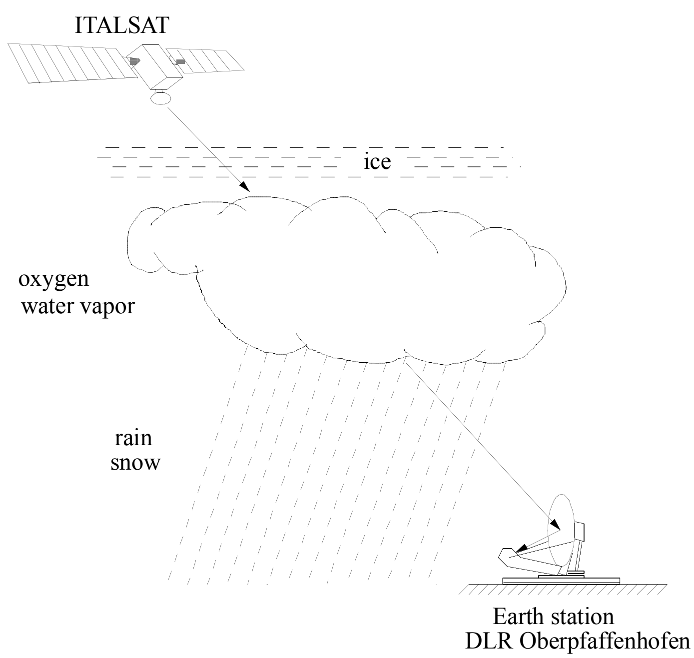
Link availability and probability of outage can be guaranteed by appropriate fade margins which, however, might become unrealistically large. In order to decrease the fade margin which is *adaptive fade mitigation techniques* can be used, such as adaptive data rate switching, adaptive modulation, or adaptive coding. Particularly when used in combination with *adaptive resource sharing*, adaptive fade mitigation techniques allow to considerably decrease the required fade margin. Adaptive resource sharing can be applied in multi-user environments. For example, considering a meshed TDMA network, adaptive resource sharing is established by use of spare time slots as a common additional resource which is shared between all stations within the network. Only stations actually suffering from attenuation are adaptively assigned parts of the common resource [*Hugo and Wilde, 1994*; *Schnell and Hugo, 1998*].

In addition to statistics on attenuation, statistics on fade duration are required to properly dimension adaptive fade mitigation techniques [*Fiebig and Schnell, 1997; Schnell and Fiebig, 1997*]. Moreover, statistics on the fade slope and the time interval during which the power level changes by a fixed amount are very useful for the dimensioning, because these statistics indicate how fast adaptive resource sharing strategies have to react [*Fiebig and Schnell, 1997*; *Schnell and Fiebig, 1997*].

5.2.2.1 Earth Station, Recording, and Evaluation Data Base

Since January 1994 the Institute for Communications Technology of DLR Oberpfaffenhofen, Germany, has been performing propagation experiments with the 40 GHz beacon of the Italian satellite ITALSAT. The objective of this campaign is to provide reliable data on channel characteristics before introducing satcom applications in these frequency bands. The channel characteristics are the basis for the determination of satellite link availability and fade margin design, and for the development of fade mitigation techniques to reduce communication link outage.

The overall scenario of the propagation measurement campaign is shown in Figure 5.2-1. The earth station site at DLR Oberpfaffenhofen is 11.3° E, 48.1° N at an altitude of 600 m above sea level. The antenna elevation angle is 34.8°. A 2.4 m diameter Gregorian offset antenna is used. It is equipped with de-icing facility, temperature stabilised feedbox, and a step-by-step tracking system. Tracking mode is switched from step-track to memory-track in case of deep fades. Recording of the downconverted received signal is carried out at baseband at 20 Hz sampling rate and is organised in 6.4 second blocks.



The sampled data are stored in *monitoring files* and *event files*. A monitoring file contains data from a whole day whereas an event file typically is of shorter duration. Only a small fraction of the sampled data (every 128th sample) is stored in monitoring files whereas event files contain all sampled data. Event files are created when the received beacon level falls below a pre-set threshold - set to 5 dB below clear sky level - and are closed when the received beacon level exceeds this threshold.

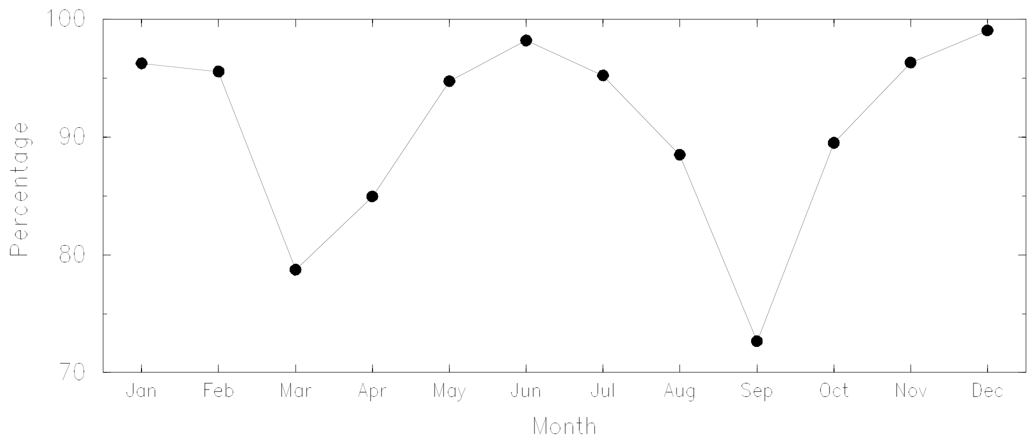


Figure 5.2-2: Recorded-to-total time ratio of the DLR propagation measurement campaign as a function of the month.

The evaluated period is the 4 years from 1994 to 1997. The recorded-to-total time ratio in Table 5.2-1 gives the total amount of useful recording time with respect to the total elapsed time.

Year	1994	1995	1996	1997	1994-1997
Recorded-to-total time ratio	89.8%	96.1%	90.3%	86.9%	90.8%

Table 5.2-1: Recorded-to-total time ratio for the years 1994 until 1997.

Figure 5.2-2 shows the recorded-to-total time ratio as a function of the month, Figure 5.2-3 gives this ratio as a function of the time of the day. All times are given in UTC, i.e. in winter 1 hour, in summer 2 hours have to be added to obtain local time. We see that in March/April, in October/November and during the night between 23:00 UTC and 01:00 UTC considerably less data has been recorded than during other periods. This is due to the fact that ITALSAT switches off the 40 GHz beacon during eclipses which happen around the equinoxes for up to about 100 consecutive minutes a day between 23:00 UTC and 01:00 UTC. Beacon has been switched off during eclipses according to Table 5.2-2.

Year	1994	1995	1996	1997
Periods with beacon off during eclipse	Feb.26-Apr.13 Aug.30-Oct.15	Feb.26-Apr.12 Aug.30-Oct.15	Feb.26–Apr.14 Aug.30-Oct.15	Feb.25–Apr.11 Aug.30-Oct.14

Table 5.2-2: Days of eclipses with beacon off for the years 1994 until 1997.

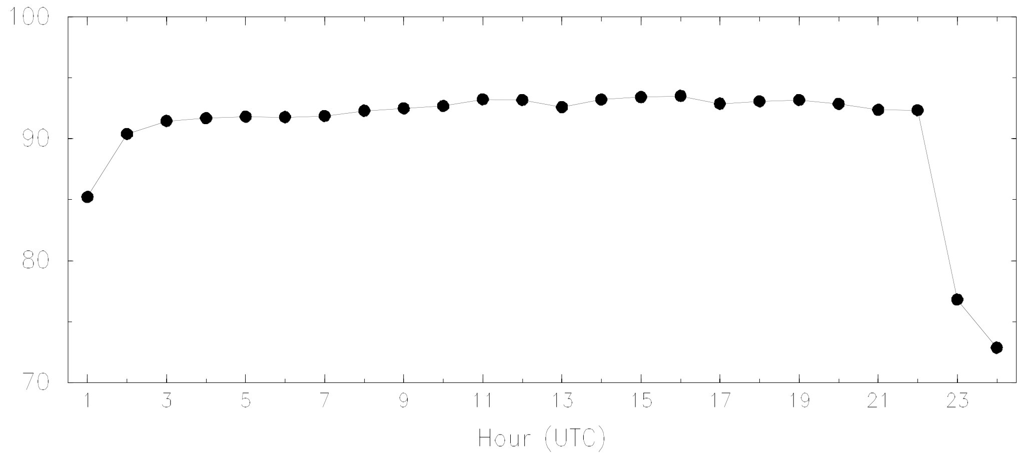


Figure 5.2-3: Recorded-to-total time ratio of the DLR propagation measurement campaign as a function of the time of the day (in hours in UTC).

5.2.2.2 Cumulative Distribution of Attenuation

Statistical Evaluation

Figure 5.2-4 gives the cumulative distribution of attenuation for each of the 12 months January to December, where the data base for each monthly statistic is the respective 4 months of the period 1994 to 1997. Furthermore, the cumulative distribution of attenuation is shown for the whole period 1994 to 1997.

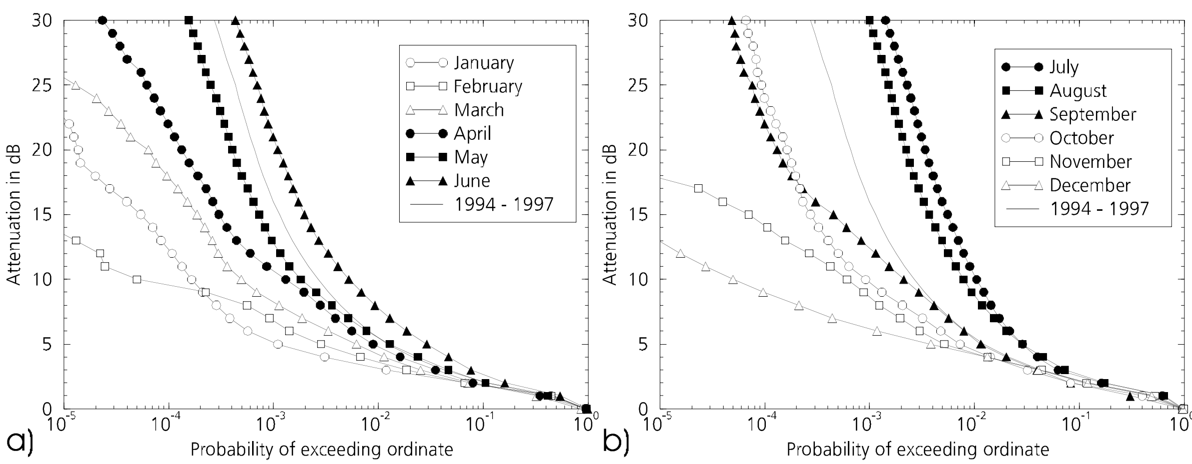


Figure 5.2-4: Seasonal variations of the cumulative distribution of attenuation:
(a) the 6 months January to June;
(b) the 6 months July to December as obtained in the 4 year period 1994 to 1997.

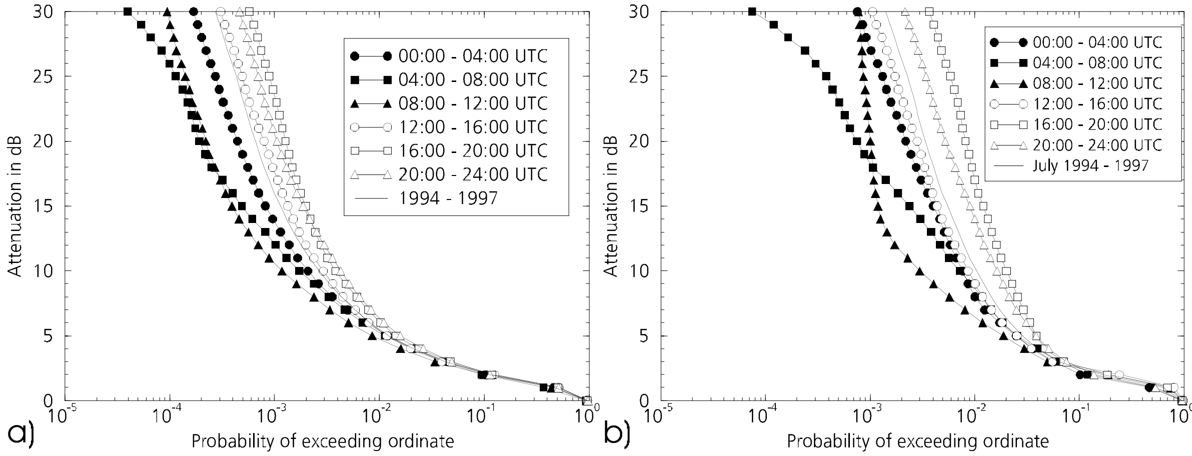


Figure 5.2-5: Diurnal variations of the cumulative distribution of attenuation; all times given in UTC: (a) 4 year period 1994to 1997; (b) July 1994, July 1995, July 1996, July 1997.

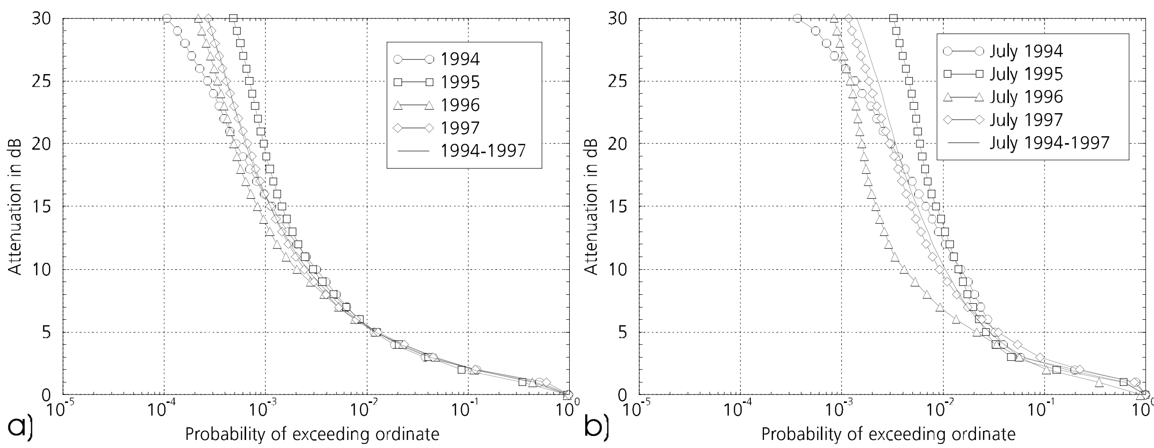


Figure 5.2-6: Variation of the cumulative distribution of attenuation from year to year. (a) for the years 1994 to 1997; (b) for the month July in the years 1994 to 1997.

It can be seen that attenuation strongly depends on the season and that June, July, and August provide the largest amount of attenuation. Figure 5.2-5 shows the diurnal variations of the cumulative distribution of attenuation. We see that the largest amount of attenuation is expected in the evening hours; this effect is most dramatic in the summer, especially in July. Note that the time is given in UTC, i.e. 1 hour has to be added to obtain local time in the winter, but 2 hours have to be added to obtain local time in the summer.

From Figure 5.2-6 we see that the cumulative distribution of attenuation may differ considerably from year to year. Thus, the fade margins which are obtained from the figures above are valid for an average year, but do not necessarily fit with the characteristics of a specific year. Weather conditions are subject to many variations. There are wet and dry years causing more, respectively less attenuation of the received signal than expected on average. Weather conditions in Germany can change significantly from year to year, especially in summer periods which provide most of the thunderstorms (and mostly these thunderstorms are responsible for deep fades). We see that July 1995 experienced severe attenuation, in contrast to July 1996 where less than average attenuation was observed. Also in the winter, attenuation may change from year to year. This is due to the fact that precipitation in the winter can be all month long, in the form of dry snow, causing only little attenuation, but also in the form of rain in warmer years causing a large amount of attenuation. Figure 5.2-7a reveals this fact, showing the differences between the various curves obtained for January. Not only seasonal but also diurnal statistics are subject to variations, see Figure 5.2-7b. In

1995 attenuation between 18:00 UTC and 20:00 UTC was considerably larger than in the other three years under observation.

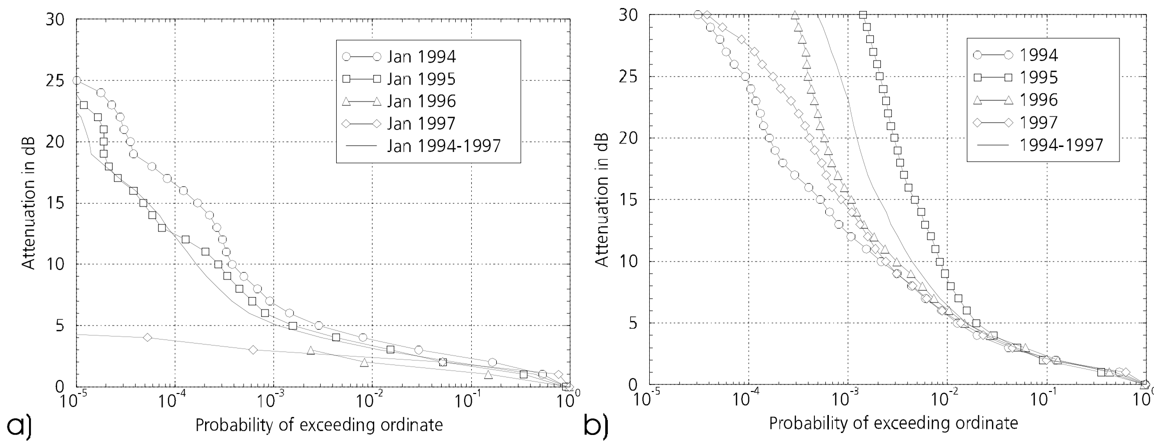


Figure 5.2-7: Variation of the cumulative distribution of attenuation from year to year: (a) for the month January in the years 1994 to 1997; (b) for the period 18:00 UTC to 20:00 UTC in the years 1994 to 1997.

Impact on System Design

From the figures shown above it is obvious that fade margin design depends not only on the required availability but also very much on season and time of the day. Figures 5.2-8 and 5.2-9 give the fade margin in dB which must be implemented to guarantee various levels of availability from 95% to 99.99%. Table 5.2-3 gives the required fade margin in dB to guarantee the various levels of availability during the four year period from 1994 to 1997.

Availability	95%	99%	99.5%	99.9%	99.95%	99.99%
Fade margin in dB (00:00 – 24:00 UTC)	2.7	5.3	7.5	15.9	23.1	39.0
Fade margin in dB (06:00 – 16:00 UTC)	2.6	4.9	6.6	13.3	18.5	25.4
Fade margin in dB (18:00 – 20:00 UTC)	2.9	6.2	9.1	22.8	29.7	41.1

Table 5.2-3: Required fade margin in dB to guarantee the various levels of availability during the 4 year period 1994 to 1997.

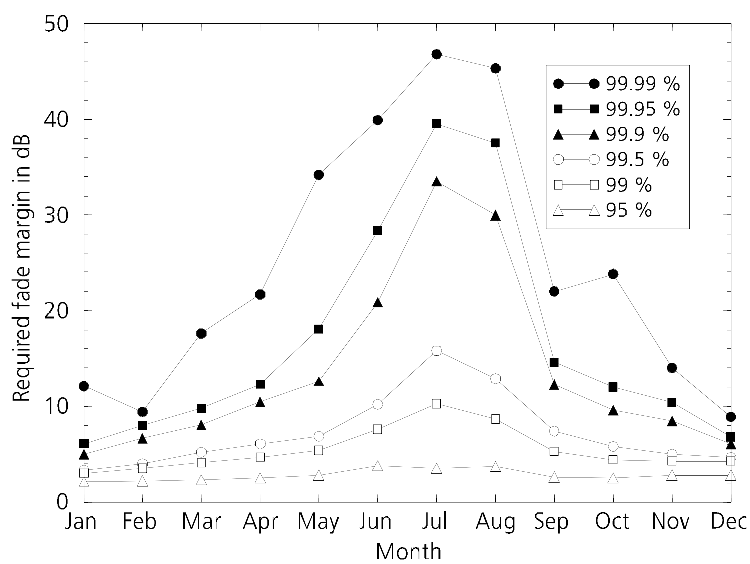


Figure 5.2-8: Required fade margin for various levels of availability as a function of the month;

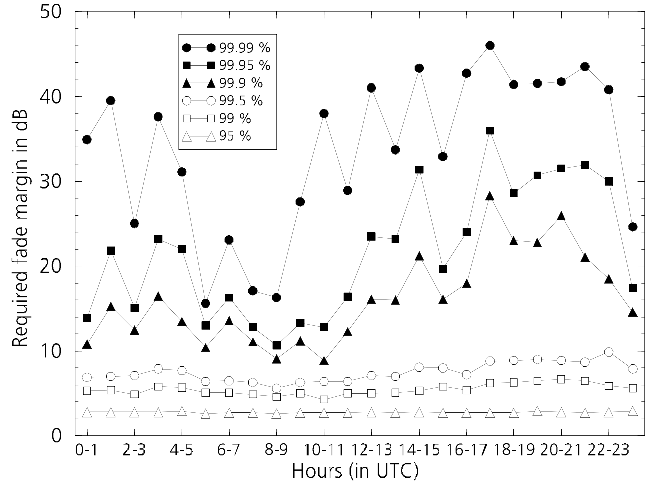


Figure 5.2-9: Required fade margin for various levels of availability as a function of the hour of the day; data basis is the period 1994 to 1997.

We see that systems are likely to be designed in a totally different manner depending on when a service is offered. There is a large difference in fade margin, depending on whether a service has to fulfil the availability requirement on average over a whole year or for a particular month or at a particular time of the day. A relatively small fade margin is required when availability has to be guaranteed during the winter months. However, a large fade margin up to 20 or 30 dB and more has to be implemented when a high degree of availability is required during the summer months. Fade margin becomes even higher when the service operates solely in the summer and in the evening hours.

5.2.2.3 Fade Duration

Statistical Evaluation

Fade duration is defined as the time duration during which attenuation is always larger than a certain threshold value. The average number of fades expected per month depends on the fade duration and the threshold value. In Figures 5.2-10 and 5.2-11 the average number of fades is plotted as a function of the threshold value; parameter is the fade duration. We see from these figures that the average number of fades per month has a tendency to decrease with increasing threshold: The larger the threshold, the fewer fades are observed.

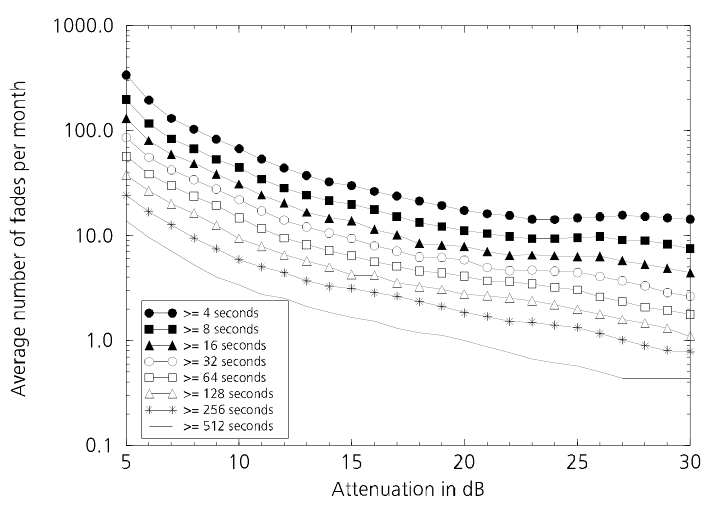


Figure 5.2-10: Average number of fades per month as a function of the threshold value (attenuation) in dB

Furthermore, we can say that the average number of fades per month has a tendency to decrease with increasing fade duration: The longer the fade duration the fewer fades observed.

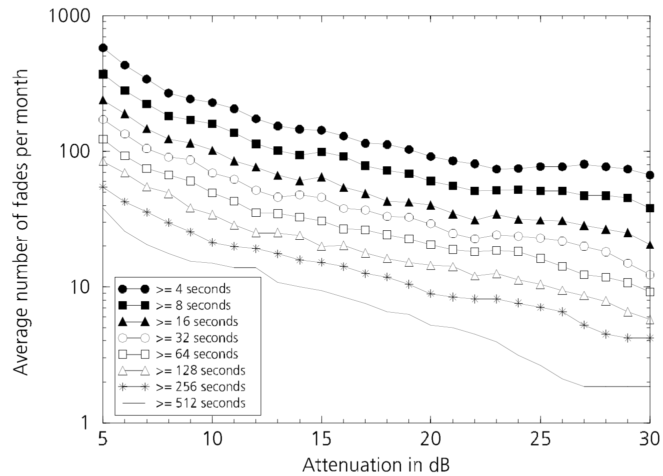


Figure 5.2-11: Average number of fades per month as a function of the threshold value (attenuation) in dB for an average July; evaluated months: July 1994, July 1995, July 1996, and July 1997.

Impact on System Design

Instead of taking availability as the basis for the fade margin design, the fade duration statistics can be used in accordance with the requirement of the service in question. The requirement could. for instance. be that a specific fading duration should be exceeded only a few times per month. For instance, if a fading duration of more than about 30 seconds should be tolerated at most 20 times per month, a fade margin of about 11 dB has to be implemented. As above, seasonal variations cause the expected number of fades per month to vary considerably over the year. In summer, fades are expected to occur considerably more often than during other seasons. Following the above example a fade margin of about 27 dB has to be implemented if a fade duration of more than about 30 seconds should not occur more than 20 times in July.

5.2.2.4 Probability of Outage

Statistical Evaluation

Given the recorded power level time-series $f(k)$ and the clear-sky value f_{cs} , the attenuation level time-series $a(k)$ is obtained as

$$a(k) = f_{cs} - f(k) \qquad 5.2\text{-}1$$

Note that the attenuation level time-series $a(k)$ takes on non-negative values, since $f_{cs} \geq f(k)$ for all time-instances *k*. In order to define the probability of outage, consider an attenuation level *x*, a time-duration τ, and a time-interval $[T_s, T_e]$ with T_s and T_e being the starting and ending points of the time-interval, respectively. The probability of outage $P_\tau^{(out)}(x,[T_s,T_e])$ is defined as the probability that within $[T_s,T_e]$ there exists a time-interval $\Delta t > \tau$ during which the attenuation level time-series $a(k)$ always exceeds the attenuation level *x*:

$$P_\tau^{(out)}(x,[T_s,T_e]) = P\{\exists\, \Delta t > \tau \mid a(k) > x \text{ during } \Delta t \wedge \Delta t \in [T_s,T_e]\} \qquad 5.2\text{-}2$$

Considering the probability of outage in more detail, the meaning of the parameters τ, x, and $[T_s, T_e]$ becomes evident:

Link margin:
The parameter x determines the attenuation level which is critical for the satellite link. If attenuation exceeds this level x, the satellite link is interrupted. Thus, the parameter x can be viewed as the link margin which is foreseen for the satellite link and is a system design parameter.

Diurnal variations:
The time-interval $[T_s, T_e]$ can be used to reflect diurnal variations by choosing appropriate values for T_s and T_e. Moreover, the duration of that interval can be adjusted. In this section, time-intervals of duration two hours are considered. This is a typical value for the duration of a film or sporting event.

Providers' point of view:
The parameter τ is the time-duration of an outage the users may be willing to tolerate during $[T_s, T_e]$, i.e. during a 2-hour time-interval, e.g. a film or sporting event. This aspect is especially interesting for providers since the probability of outage can be determined as a function of τ and, therefore, as a function of the users' requirements.

Impact on System Design

Figure 5.2-12 gives the probability of outage as a function of x for the time interval [18, 20] UTC for both the summer months June, July, and August, and for an average year. The time is in UTC, i.e. 2 hours has to be added in the summer yielding local time 8 p.m. to 10 p.m. This is the favourite time for films and sporting events which typically last 2 hours. It can be seen that the probability of outage decreases with increasing τ and increasing attenuation.

Length of outage in minutes	1	5	10	1	5	10
	All year			summer		
Fade margin in dB	4.8	5.5	7.2	7.8	9.8	15.0

Table 5.2-4: Required fade margin in dB to guarantee that probability of outage is below 5%.
Data basis is the 4 year period 1994 tol 1997.

If a service provider guarantees that the outage probability is on average lower than 5% between 8 p.m. and 10 p.m.(local time), and if outage is defined as a continuous interruption of the communications link of more than 5 minutes, then a fade margin of 9.8 dB has to be implemented. Table 5.2-4 gives the fade margins for various scenarios.

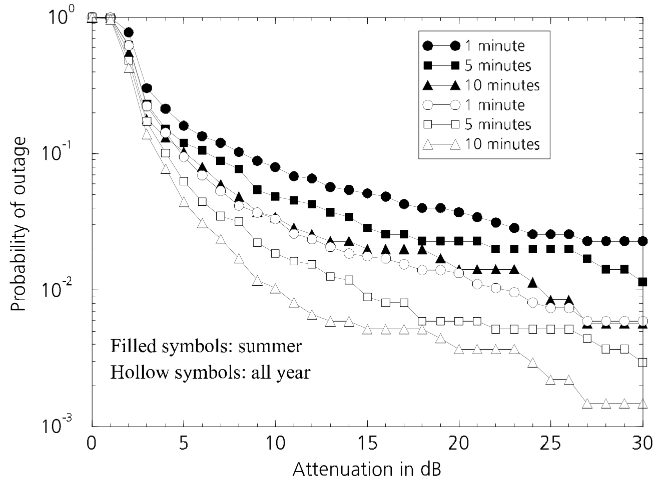


Figure5.2-12: Probability of outage as a function of x for the time interval [*18, 20*] *UTC; summer months June, July, and August, and all year statistics; data basis is the 4 year period 1994 to 1997.*

5.2.2.5 Fade Slope and 3dB Time Duration

In order to derive statistics on fade slopes we focus on fade events. They are recorded in event files and contain the relevant data to answer the questions: What fade slopes have to be expected? What are the maximum fade slopes observed? Before analysing the event files the recorded signal is low pass filtered in order to remove fluctuations that are caused by scintillation. Low pass filtering is realised by a weighted moving average. The time window for averaging is set to $T_{av} = 10$ sec, thus, spanning $N_{av} = 201$ recorded values. The discrete weighting function $h_{av}(k)$ is chosen to be a squared cosine halfwave

$$h_{av}(k) = \begin{cases} \cos^2\left(\dfrac{\pi \cdot k \cdot T_a}{T_{av}}\right) & -100 < k < 100 \\ 0 & \text{otherwise} \end{cases} \qquad 5.2\text{-}3$$

where T_a is the sampling period which is 20 Hz. The 3dB cut off frequency of the low pass filter is 0.1 Hz, removing almost all scintillation. After low pass filtering the time window is shifted by 20 samples instead of one, in order to perform a downsampling to $T_{ds} = 1$ sec. Thus, the filtered power level time-series denoted $f(n)$ is obtained. The derivative $f'(n)$ of $f(n)$ is then determined by

$$f'(n) = \frac{(f(n) - f(n-1))}{T_{ds}} \qquad 5.2\text{-}4$$

The fade slope is defined as the absolute value $|f'(n)|$ of the derivative at the time-instant n and gives the power level changes based on 1sec intervals.

The cumulative distribution of fade slopes is given in Figure 5.2-13, which is based on measurements carried out during June, July, and August 1996. A total of 127 fading events were recorded on 43 different days, comprising 59.4 hours which is referred to as fade event time. Figure 5.2-13 distinguishes between negative and positive slopes. As can be seen, fade slopes up to 3.2 dB/sec are observed. However, steep fade slopes of more than 2.0 dB/sec are very rare and were measured during a single fading event. In 99.99 % of the fading event time the fade slopes for both negative and positive slopes are less than 1.9 dB/sec. Figure 5.2-13 indicates that negative and positive slopes are equally likely. This is a surprising result, since it has been observed that time interval of duration 1 sec. The observation that "attenuation increases faster than it decreases" can be shown when considering time intervals of longer duration. It is the 3dB time duration introduced below which reveals the differences between positive and negative slopes.

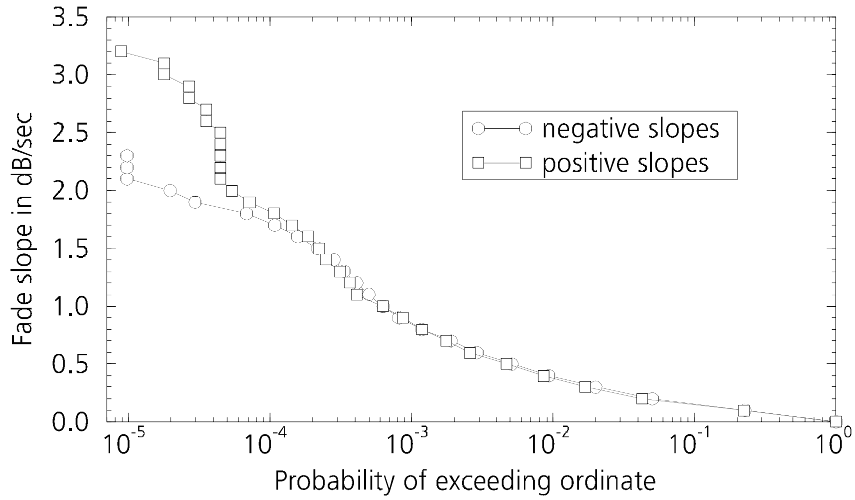
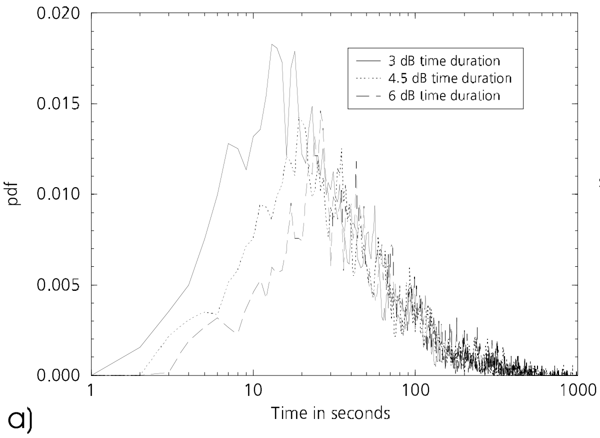


Figure 5.2-13: Cumulative distribution of positive and negative fade slopes as observed during deep fades in the months June, July, and August 1996.

The 3 dB time duration $T_{3\text{dB}}$ is defined as the time interval during which the power level changes by 3 dB and is determined in the following manner: For every time-instant n of the low pass filtered fading event with power level $f(n)$, the next possible time-instant $m>n$ with power level $f(m)$ is determined which satisfies the relation $f(n)-f(m)>3\,\text{dB}$ for a negative slope and $f(n)-f(m)<3\,\text{dB}$ for a positive slope. A value of 3 dB is chosen for the power level change, taking into account typical switching thresholds for satellite systems which apply advanced fade mitigation techniques [*Hugo and Wilde, 1994*; *Schnell and Hugo, 1998*]. However, these fade mitigation techniques also operate with other thresholds and so values of 4.5 dB and 6 dB are also considered. The respective time durations are denoted $T_{4.5\text{dB}}$ and $T_{6\text{dB}}$.

The probability density functions of $T_{3\text{dB}}$, $T_{4.5\text{dB}}$, and $T_{6\text{dB}}$ obtained during the fading event time in June, July, and August 1996 are given in Figure 5.2-14 for both negative and positive slopes. As can be seen, the probability density functions for values smaller than 20 seconds are about twice as large for negative slopes as for positive slopes indicating that "attenuation increases faster than it decreases" on average. This is consistent with the observation that heavy rain fall usually sets in more abruptly than it stops. Another result from Figure 5.2-14 is that a considerable number of power level changes of 3dB occur within a few seconds.



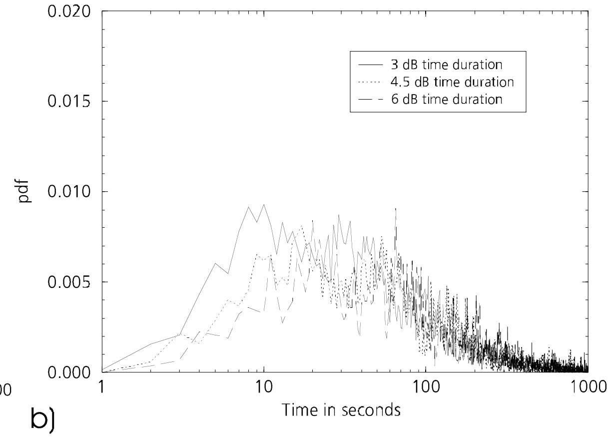


Figure 5.2-14: Probability density function of T_{3dB}, $T_{4.5dB}$,and T_{6dB} obtained during the fading event time in June, July, and August 1996: a) for negative fade slopes; b) for positive fade slopes.

5.2.3 Influence of Phase Noise and Sky Noise Temperature; Constraints for Future Portable (Laptop) VSATs

This section analyses the limitations in the phase error of a PLL carrier acquisition system when the spectral purity of the carrier arriving from the satellite is limited by the irreducible phase noise introduced by the atmosphere (turbulence). The section analyses also the ultimate limitation in achieving a high C/N_o factor as imposed by the atmospheric noise temperature when the system front end noise becomes progressively smaller permitting the use of very small aperture terminals (laptop-VSAT). An overview of the whole subject area can be found in [*Senin et al., 1997*] and the experimental results refer to the Portsmouth ITALSAT research programme and system [*Vilar et al., 1997*].

5.2.3.1 Carrier Acquisition in the Presence of Propagation Phase Noise and Thermal Noise

Referring to Figure 5.2-15, the variance of the noise detector phase output of a PLL is:

$$\sigma^2(\theta_e) = \sigma^2(\theta_{en}) + \sigma^2(\theta_{ep}) = \int_0^\infty \frac{N_o}{C}\left|\mathrm{H}(j\omega)\right|^2 df + \int_0^\infty S_\phi(f)\left|1-\mathrm{H}(j\omega)\right|^2 df \qquad (\mathrm{rad}^2) \qquad 5.2\text{-}5$$

where the subscripts n and p refer to thermal noise and phase noise respectively.

If the phase noise power spectral density $S_\phi(\phi)$ can be modelled as A/f^{b+2} rad²/Hz (so that $S_{\dot\phi}(\phi) = A/f^b$ Hz²/Hz) then, in the case of a second order PLL with damping factor $1/\sqrt{2}$ and b=5/3 (propagation phase noise [*Vilar and Catalan, 1998*]):

$$\sigma^2(\theta_e) = \sigma^2(\theta_{en}) + \sigma^2(\theta_{ep}) = \mathrm{B}_L\frac{\mathrm{N}_0}{C} + 5.283\frac{\mathrm{A}}{\mathrm{B}_L^{5/3}} \quad (\mathrm{rads}^2) \qquad 5.2\text{-}6$$

where B_L = PLL loop bandwidth.

In the case of frequency flicker noise the second term becomes $8.71A/B_L^2$ (for Italsat F40, A was 0.1). For white frequency noise we get $3.7A/B_L$. Therefore the propagation phase noise fills the gap between flicker fm noise and white fm noise. Figure 5.2-15 contains also a parametric study of Equation 5.2-6. Two extreme values of the propagation parameter C_n^2L have been selected which index structure constant C_n^2 ($m^{-2/3}$), the effective turbulent path L (m) (usually the top of turbulent clouds), the average cross path wind v (m/s) and the carrier frequency f_c (GHz) is given by $A = 851 f_c^{\,2} v^{2/3} C_n^{\,2} L$. Figure 5.2-15 indicates that if C/N$_o$ is low, the dominant part is the thermal noise $\sigma^2(\theta_{en})$. As the signal strength increases so that C/N$_o$ increases and/or the loop bandwidth B_L is reduced to track better the carrier and reduce $\sigma^2(\theta_e)$, the phase noise component $\sigma^2(\theta_{ep})$ can become the dominant term. There is an optimum B_L which minimises Equation 5.2-6 and is given by $B_L = (8.8AC/N_0)^{3/8}$ Hz for the case of propagation phase noise.

Other types of noise exhibit similar dependence.

The parametric study of Figure 5.2-15 is essential for future laptop terminals; with current satellite transmitter EIRPs, the operational C/N$_o$ may well lie in the range 45 to 55 dBHz. Other slightly larger antennas may give 50 or 55 dBHz or even 60 dBHz. However, N$_o$ is limited by the front-end noise and the ”irreducible” atmospheric noise temperature (clouds particularly). For good carrier recovery $\sigma^2(\theta_e)$ should not exceed 0.1 rad rms (about 6º). From Figure 5.2-15 it follows that one has to reduce the loop bandwidth down to an optimum. If the satellite on board transmitter has negligible phase noise, the only remaining ”irreducible” phase noise is that due to propagation. Most of the time A will be small and it will be possible to keep the loop bandwidth down to about 10 Hz or even less giving a very low phase error in the recovered carrier except for the “bursts” of propagation phase noise. Figure 5.2-15 shows that phase errors of 0.1 rad rms at 20 GHz (downlink) will not be exceeded in a very small portable system having a C/N$_o$ as low as 45 dBHz and a B_L of about 100 Hz. Therefore carrier acquisition with a “clean” transmitter carrier will not be a problem.

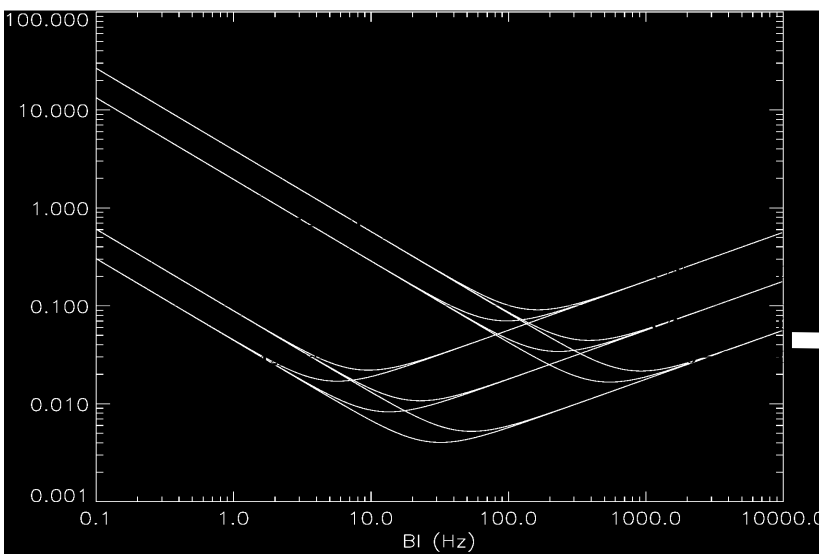


Figure 5.2-15: Phase error noise at the PLL detector output due to thermal noise and phase noise.

Atmospheric Degradation of C/No for Low Noise Systems

Although there would be no problem in carrier recovery and reducing the system front-end noise to negligible levels (20 GHz preamplifiers with Noise Figure, NF, as low as 1 dB are becoming commercially available) one must bear in mind that the impact of the atmospheric noise on C/N$_o$ becomes more important as the NF of the receiver is reduced [*Catalan and Vilar, 1998*].

an improvement of 10 dB. Unfortunately, as the system noise decreases in the presence of fades the improvement of C/N_o is not as high as expected, due to the relative contribution of the atmospheric thermal noise. The degradation Δ in C/N_0 with respect to clear sky $\left[C/N_0\right]_c$ is:

$$\Delta[dB] = \left[\frac{C}{N_0}\right] - \left[\frac{C}{N_0}\right]_c = A - A_c + 10\log_{10}\left[1 + \frac{T_{sky}/T_{sky}^{clear} - 1}{T_{sys}/T_{sky}^{clear} + 1}\right] \quad 5.2\text{-}7$$

where:

A = Total atmospheric attenuation

A_c = Clear sky attenuation

T_{sky} = Sky brightness temperature

T_{sky}^{clear} = T_{sky} in clear sky (35 K at 20 GHz and 30^o elevation)

T_{sys} = System noise (290*(10$^{NF/10}$-1)).

The relative importance of the third term of Equation 5.2-7 is shown in Figure 5.2-16.

For the above example a 6 dB fade results in a 6 dB reduction in C/N_o using a receiver with a 7 dB noise figure. However it results in a 10.2 dB reduction in C/N_o using a receiver with a 1 dB noise figure. Thus in the presence of a 6 dB fade, the absolute improvement in C/N_o is not 10 dB but 5.8 dB. As the fading increases the improvement in this case tends to 5 dB.

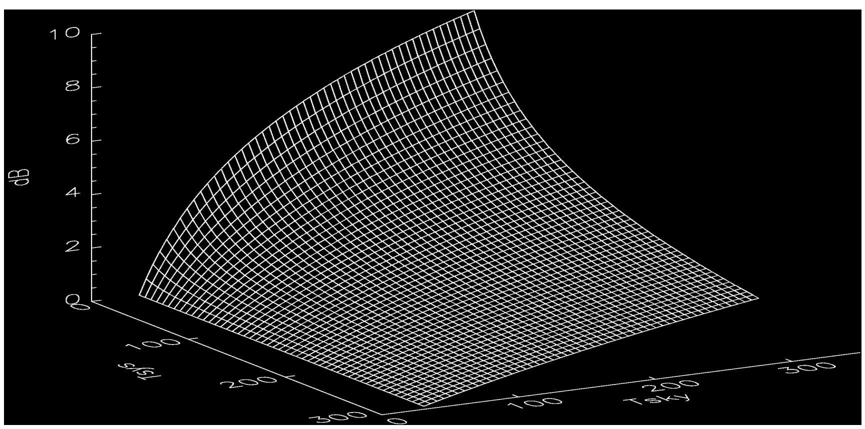


Figure 5.2-16: Degradation in C/No due to atmospheric thermal noise for low noise temperature.

5.2.4 Conclusions

Both the propagation effects as well as the system design of future satellite systems are considered in this chapter. Especially, the impact of propagation impairments on the design of future satellite systems has been investigated.

In Section 5.2.2 the impact of atmospheric attenuation on the system design is considered using cumulative distributions of attenuation, fading length statistics, the probability of outage, fade slope statistics, and the 3 dB time duration for statistical evaluation. The necessary link margins are determined for different satellite service requirements and discussed taking into account that atmospheric attenuation at 40 GHz may be temporarily very strong and that it shows strong seasonal as well as diurnal variations. The statistical evaluation of the cumulative distribution of very much on season and time of the day. Summer months require a considerably larger link margin than winter months when the same availability has to be guaranteed. Furthermore, evening hours require a larger link margin than other times of the day. If service requirements other than availability have to be satisfied, the fade duration statistics and the probability of outage are valuable link margin design data. The link margin for the requirement that a specific fading duration should be exceeded only a few times per month can be evaluated using fading duration statistics. The probability of outage is used to determine the link margin necessary to guarantee that an intolerably long outage is unlikely to occur during a certain period, e.g. during a film or sporting event. If high availability or low probability of outage is required, especially for a certain season or time of the day, extremely large link margins, which might be 30 dB or more, have to be implemented. Since large link margins are too expensive to implement, fade mitigation techniques together with a sophisticated adaptive resource sharing strategy should be applied for future satellite systems operating in the higher frequency range. To properly design fade mitigation techniques, fade slope statistics and 3 dB time duration are proposed. Both evaluation statistics can be used to determine the required dynamic behaviour of fade mitigation techniques.

In Section 5.2.3 the influence of phase noise and sky noise temperature on future portable (laptop) VSATs is investigated. In particular it is shown that by augmenting the spectral purity of the satellite on-board transmitter one can decrease the loop bandwidth of the carrier acquisition system (PLL). However, there is a limitation imposed by the irreducible propagation phase noise, which has been quantified in Section 5.2.3. Moreover, it is shown that atmospheric noise limits the improvement achievable by increasing the noise performance of the microwave front end of the VSAT receiver. Therefore, the relative improvement in C/N_o brought about by substantially reducing the receiver noise figure results in a variability (sensitivity) $\Delta C/N_0$ greater than the variability in attenuation. As a result, if the receiver noise figure is reduced substantially, the C/N_0 improves but can fluctuate more than the atmospheric attenuation.

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CHAPTER 5.3
Impairment Mitigation and Performance Restoration

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5.3 Impairment Mitigation and Performance Restoration

Satellite communications present some significant advantages over terrestrial networks, such as flexibility and reconfigurability of the network, the possibility to establish point-to-multipoint links (broadcasting, mobiles…). Therefore communication satellites need to be integrated with terrestrial networks, and should provide high data rates. To carry such high data rates, higher frequencies should be considered, such as Ka-band (20 GHz - 30 GHz), V-band (40 GHz - 50 GHz) or EHF-band (20 GHz - 45 GHz). These offer large bandwidths that are not available at L to Ku band. For some years, innovative satellite systems have been proposed, either in Ka or V band for civil applications (Cyberstar, Euroskyway, Skybridge 2, Skystation, Teledesic, West…) or in EHF band for military applications (ST3SII, GFSatCom, Skynet, Milstar).

One of the problems raised by these new frequency bands is how to quantify precisely the influence of the atmosphere on the propagation of electromagnetic waves. Due to technology limitations, system margin can no longer be considered as the sole means to compensate propagation disturbances at any percentage of time.

Some preliminary studies have demonstrated that the feasibility of such links seems to be guaranteed. However, it is now necessary on the one hand to determine which level of service availability will be supplied to the user, and on the other hand to investigate the behaviour of these anticipated systems when subject to the severe fading conditions encountered at frequencies above 20 GHz.

As it is not cost efficient to design a large power margin, link signal fading must be compensated by other means in order to increase system availability. These alternatives, which overcome fading without the use of large fixed margins, are known as Fade Mitigation Techniques (FMT) or Fade Counter-Measures (FCM).[1]

With such techniques, it will, for instance, be possible to design VSAT systems with a fixed margin corresponding to the worst case of fading occurring in clear-sky conditions; the implementation of FMT allowing to counteract, in real time, cloud attenuation, some fraction of rain attenuation, scintillation, and depolarisation events.

The objective of this chapter is to give an overview on the application of FMT. It is organised in two main sections: firstly a state-of-the-art report of FMT, and secondly a synthesis of the developments carried out in this field in the framework of COST 255 Working Group 3.

Moreover, the propagation issues of the operational implementation of FMT, and especially the problem of detection, control and prediction, are laid down. Three detection schemes: open-loop, closed-loop and hybrid-loop are investigated and compared, and recommendations are given on their suitability in relation to the frequency band.

5.3.1 FMT: state-of-the-art report

This review has been done without considering specific system architecture and multiple access schemes and only gives a description of FMT. Fade detection and prediction, which are related topics to be considered to implement FMT techniques, are beyond the scope of this chapter.

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1 in the following, these techniques will be referred as Fade MitigationTechniques (FMT) rather than the term Fade Countermeasures usually used in the literature, but which has a typical radar signification. Indeed, a countermeasure is an active technique aimed to cause interference to an opposing system. If the intention is to use the radar language,

5.3.1.1 Presentation of FMT

Various methods exist to mitigate propagation effects and the choice of the most relevant ones should take into account operating frequency bands, the performance objectives of the system and the geometry of the network (system architecture, multiple access schemes…) [*Willis and Evans, 1988*; *Tartara, 1989*; *Allnutt and Rogers, 1993*; *Gallois, 1993*; *Acosta, 1997*].

It is possible to divide FMT into three categories: Power Control, Signal Processing and Diversity FMT.

Power Control and Signal Processing FMT are characterised by the sharing of unused (excess) system resources, whereas diversity FMT implies adopting a re-routing strategy. Sharing unused resources aims to compensate fading occurring on a particular link in order to maintain or to improve the link performance (C/N_0), whereas diversity techniques maintain link performance by changing the frequency band or the link geometry.

It is possible to distinguish three types of Power Control FMT: Up-Link Power Control where the output power of a transmitting Earth station is matched to up-link or down-link (in case of non-regenerative transponder) impairments, Down-Link Power Control where the on-board repeater output power (before the antenna) is adjusted and On-Board Beam Shaping which consists of changing on-board antenna radiation patterns. Down-Link Power Control and On-Board Beam Shaping (for transmitting antenna) can be considered as Satellite EIRP Control techniques.

As far as Signal Processing FMT is concerned, two classes of methods can be identified which lead to a modification of the sharing of the satellite resources by acting on the information data rate or on the bandwidth. The objective of the first class is to introduce extra coding in order to compensate additional attenuation on the link by maintaining the nominal BER or to change modulation schemes to implement more robust modulations requiring less symbol energy. A second class of techniques aims to reduce the information data rate at constant transmission data rate, which also leads to maintaining the BER.

Finally, Diversity FMT results in setting up a new link: Frequency Diversity permits, among different payloads on a satellite system, to choose the payload whose frequency band is the least affected by the meteorological situation, whereas geometrical (Site or Satellite) Diversity avoids an atmospheric perturbation which is going to produce a fade. Site diversity consists in transmitting the information through a second link less affected by propagation conditions and afterward to re-route the information to the first destination by another path (for instance by a terrestrial network). Satellite diversity can be carried out within a satellite constellation, in order to choose the satellite that offers the link with the highest service quality.

5.3.1.2 Description of the main fade mitigation methods

As already stated in the previous paragraph, FMT can be divided into 3 classes:

- Power Control FMT: transmit power level matched to propagation impairments,
- Signal Processing FMT: fade compensated by making use of a more efficient communication scheme,
- Diversity FMT: fade avoided by the use of another, less disturbed, link.

Power Control techniques

In the case of transparent bent pipes, the goal of Power Control is not only to adapt transmitted power to counteract uplink fading, but in a more general way, to adapt power in order to optimise the overall C/N_0.

Power Control can be carried out at two locations: first on the ground segment where the output power of a transmitting Earth station is adapted to up-link and this is named Up-Link Power Control (ULPC); secondly, on-board the satellite, which leads either to the concept of Down-Link Power Control (DLPC) which acts on the satellite transmitter power in front of the transmit antenna or to the concept of On-Board Beam Shaping (OBBS) which aim is to adjust antenna patterns as a function of propagation conditions and as a function of the traffic.

Up-Link Power Control (ULPC)

The aim of power control is to adapt the carrier power level to the propagation conditions. To demonstrate the interest in ULPC, it is necessary to distinguish the cases of transparent and regenerative repeaters.

<u>Transparent repeater</u>

In the case of a transparent repeater, the adaptation of the carrier power level by the transmitting Earth station acts on both uplink and downlink budgets [*Hörle, 1988*]. As far as the uplink is concerned, ULPC adjusts the transmitted power of the Earth station either to transmit the minimum required power in clear sky conditions or to compensate propagation impairments to maintain the uplink budget. Then, the Earth stations which does not suffer from propagation impairments are able to operate without rain margin. When an ULPC technique is implemented, it is not necessary to consider link power margins (to compensate for rain attenuation) in the design of the system, which translates into a higher system capacity.

The influence of ULPC on the downlink budget can be considered in two ways: firstly in avoiding reductions of satellite EIRP caused by the decreased uplink power level that would occur in the absence of ULPC, secondly in compensating downlink propagation impairments, if the repeater dynamic range between the operating point and the saturation level (maximum power) is sufficient [*Egami, 1982*], i. e. if the satellite power amplifier is not operated at full power.

In addition, in a multicarrier environment, [*Dodel and Riedl, 1991*] have demonstrated that the optimal satellite capacity is obtained if all carriers are attenuated in the same way on the uplink; the worst case corresponds to the situation in which only a few carriers are faded and suffer from a non-linear capture effect. Therefore, in a multicarrier environment, adaptation of Earth station EIRP to propagation conditions allows to keep a constant power level of all the carriers at the input of the repeater, then avoiding excessive intermodulation.

In conclusion, ULPC can be seen on the one hand as a way to keep a constant level of all the carriers at the input of the repeater, and on the other hand as a way to maintain the overall link budget of the links in order to optimise the satellite capacity.

<u>Regenerative repeater</u>

With a regenerative repeater carriers are demodulated onboard the satellite, which makes the baseband signals available for specific processing prior to the modulation of the downlink carriers. On-Board Processing (OBP) can be used to optimise the overall link budget of the system. In principle, this technique allows to match the waveform (data rate, coding rate, modulation scheme) to the propagation conditions.

However, in the case of low margin systems or for systems operating at or above Ka-Band, a static margin sufficient to prevent outages due to propagation conditions (even stratiform rains) especially on the uplink is not realistic. This is particularly the case at Ka-band or EHF-band, where there is a strong relative difference between up and down frequencies, and for which a strong protection against uplink fading is important. So the interest of ULPC is reinforced.

Furthermore, it is necessary to pay attention to the sensitivity of on-board demodulation to signal dynamic range at the input of the repeater. As FDMA is a typical choice on the uplink, if OBP is sensitive to strong variations between carriers, therefore, even for high margin systems, it is recommended to use ULPC in order to avoid capture effects of carriers faded by severe propagation conditions. In this case, the monitoring of all carrier levels has to be carried out on-board the spacecraft, before the spacecraft indicates to the appropriated Earth station the necessary adjustments of up-link transmit power [*Acosta, 1997*].

Therefore, in the case of a regenerative repeater, for low margin systems and systems operating at or above Ka-band, use of ULPC is helpful in order to prevent system capacity degradations due to propagation conditions.

In conclusion, Up-Link Power Control makes use only of transmitted Earth station power; without constraints on the sharing of the system resource and without a need for specific delay before mitigation. This argument makes this technique a very flexible one.

Down-Link Power Control (DLPC)

DLPC [*Acosta, 1997*; *Karasawa and Maekawa, 1997*] aims to allocate a relatively small amount of extra-power on-board (due to limitations in TWTA output power), in order to compensate a possible degradation in term of down-link C/N_O due to propagation conditions in a particular region. In this case, all Earth stations in the same beam coverage benefit from the improvement of EIRP.

This technique applies only if the transponders are designed in such a way that very little adjacent channel interference and intermodulation noise are produced by the increased transmitted power. Furthermore, it is necessary to verify on the one hand that the ground power flux density specification is not exceeded (to cope with radio-regulation and to avoid interference problems), and on the other hand that no service outage occurs during changes in power level.

An estimate of the benefit obtainable by the DLPC can be obtained by comparing the two curves giving the outage as a function of the system power margin when this is allocated in a uniform or optimised way. From these two curves two parameters can be obtained, the *adaptivity gain* and the *adaptivity improvement*, whose meaning is similar to the one defined in the case of space diversity: the dBs spared to have the same outage in the first case, or the ratio of the lost users for the same margin, in the second.

On-Board Beam shaping (OBBS)

This technique is based on active antenna flexibility, which permits the adaptation of spot beams to propagation conditions [*Poiares-Baptista and Paraboni, 1995*]. If the meteorological situation in a particular area can potentially cause fading by degrading the link quality of the Earth stations located in this zone, it is possible, with active antennas, to adjust the satellite antenna gain by reducing the size of the spot beam pointing to this region. In fact, the objective is to radiate extra-power, and to compensate rain attenuation only on spot beams where rain is likely to occur.

To apply this FMT, it is not necessary to analyse in real time the fade dynamic as for other FMT, but to realise short-term weather predictions (Nowcasting) to determine the principle of Nowcasting could be to use satellite imagery in order to analyse the evolution of the meteorological situation (cloud type and cloud motion identification, rain height and rain intensity determination…) to carry out very short-range forecasting of the propagation conditions [*Hartigan and Gallois, 1993*].

Two kinds of antennas have been considered in a study conducted by ESA [*Poiares-Baptista and Paraboni, 1995*]: a multi-feed antenna fitted with a beam-forming network with variable power dividers and a Cassegrain antenna with a single feed and two shaped reflectors with small subreflector capable of being re-shaped in orbit. The conclusion of this study is that the first solution is both more flexible and allows higher adaptive gain.

Recent simulations made by assuming a cluster composed of 8 spots fed by the same amplifier (total power constant but different powers relocatable among the spots) have demonstrated that adaptivity advantages of the order of 3 to 5 can be reached, by exploiting the variability of the weather conditions across the whole of Europe, for a system margin of 1.5 and 3 dB.

In fact, this technique appears to be interesting but it could be too expensive (in terms of development costs) for the first generation of Ka band payloads, mainly due to three kinds of problem:

- the difficulty to accommodate a relatively large antenna within the launcher fairing,
- the use of large active antennas for telecommunications purposes, due to limitations in the development of on-board technology, and the feasibility of re-shaping spot beams without penalising the global coverage; even though, for instance, the current antenna technology allows to obtain European coverage with a cluster of 32 feeds,
- the elaboration of meteorological Nowcasting, which is a very promising technique for short range propagation predictions in the frame of high frequency satellite telecommunications. However, the nowcasting accuracy is improving rapidly, both concerning the ECMWF (European Centre for Medium-range Weather Forecasting) and Meteosat. Moreover, the fact that no spatial detail below 100 km is necessary helps, indicating that a space-time accuracy is not really a stringent requirement.

The advantage of this method is that it gives similar results to ULPC or DLPC, without increasing transmit power. Furthermore it allows a better design of satellite coverage, taking account of propagation conditions but also the distribution of users in the coverage area (e.g. for mobile systems).

Signal processing techniques or Adaptive Signal Processing (ASP)

These techniques have been named Adaptive Resource Sharing because the available resources on the satellite depend on the number of users requesting a part of these resources at the same time. Actually, it would be better to use the term Adaptive Signal Processing (ASP) to distinguish them from power control FMT that can also be considered as Adaptive Resource Sharing techniques. Three kinds of adaptive methods can be distinguished: Adaptive Coding, Adaptive Modulation and Data Rate Reduction.

Adaptive Coding (AC)

When a link is experiencing fading, the introduction of coding allows to add redundant bits to the information bits, in order to detect and to correct errors (FEC…) caused by bit. Adaptive coding consists in implementing a variable coding rate in order to match impairments due to propagation conditions.

Various possibilities exist to vary coding rates; for instance the use of separate optimised codes for each data rate [*Schnell and Von Hugo, 1998*], the use of "punctured" codes [*Willis and Evans, 1988*], or of convolutional codes. A gain of typically 2-10 dB can be achieved, depending on the coding rate [*Willis and Evans, 1988*].

The fading satellite telecommunications channel does not produce independent errors but blocks of errors. Therefore most Forward Error Correcting codes are designed to improve system performances by correcting errors which are supposed to be independent, they are not very efficient in counteracting fading. The performance of the mitigation technique can be improved by using block codes (such as Reed-Solomon codes) which are more robust to bursts of errors, and with interleaving, which scrambles the coded data in such a way that, after descrambling, errors can be considered independent [*Proakis, 1995*]. Interleaving is efficient only for very short fades and especially for scintillation. Higher performances can be obtained by the concatenation of a convolutional code (Viterbi algorithm) with a block code (such as a Reed-Solomon code), the convolutional code being efficient at correcting random errors, whereas the block code is a good solution to correct error bursts.

The limitations of this FMT are linked to the additional bandwidth requirements for FDMA and larger bursts in the same frame for TDMA (due to implementation of redundancy bytes). Adaptive coding can therefore be used when the application permits reduced throughput when multiple links are experiencing fading simultaneously. In addition, transmission delays are proportionally larger for low data rate increase [*Allnutt and Rogers, 1993*], because of processing and interleaving, which makes this FMT less reactive and flexible than for instance power control techniques.

Adaptive Modulation (AM)

Higher system capacity for a specified bandwidth can be achieved by using modulation schemes with high spectral efficiency such as coded modulation or combined amplitude and phase modulation. Indeed, digital transmission with M-level digital modulations makes it possible to transmit more bits per second and yet not increase the bandwidth proportionally [*Filip and Vilar, 1990*; *Maral and Bousquet, 1998*].

As with Adaptive Coding, the aim of the Adaptive Modulation technique is to decrease the required bit energy per noise energy ratio (E_b/N_o) corresponding to a given BER, by reducing the spectral efficiency as the C/N decreases. The reduction of the spectral efficiency can be obtained by introducing lower level modulation schemes. For instance, if very efficient modulations such as 16-PSK, 64-PSK or 256-QAM can be used in clear-sky conditions, in bad propagation conditions, Adaptive Modulation FMT makes use of more robust modulations such as QPSK or BPSK [*Filip and Vilar, 1990*; *Gallois, 1993*].

This technique requires a high E_b/N_0: for instance, implementing a 16-PSK modulation scheme requires an E_b/N_0 of 24 dB to obtain a BER of 10^{-6}. Such a link budget will be difficult to establish, especially at Ka or V band.

Another way of reducing the required E_b/N_0 is to introduce coding into the modulation. This method allows to exchange spectral efficiency for power when the link experiences fading due to bad propagation conditions. New modulation schemes such as Trellis

Such a system based on adaptive pragmatic trellis coded modulation has been proposed recently [*Gremont et al., 1999a*]. The proposed FMT system can be seen as a generalised one since it encompasses adaptive coding and adaptive modulation as subsets. It is in effect a multiple FMT system relying on adaptive signal processing techniques and is suitable for services which can accept a variable user data rate (i.e. the satellite bandwidth occupancy is fixed on a channel basis). The supported modulations are convolutionally encoded BPSK/QPSK with code rates 1/2, 2/3, rate 2/3 pragmatic 8PSK and rate 3/4 pragmatic 16PSK as well as uncoded B/Q/8/16PSK. The authors showed that such a multiple FMT modem could very significantly outperform systems relying on single FMTs such as adaptive coding or adaptive (uncoded) modulation.

Data Rate Reduction (DRR)

Differently from ULPC, which aims at restoring the Carrier-to-Noise Ratio (C/N_o) through an increase of the Earth Station transmitted power, Adaptive Coding (AC), Adaptive Modulation (AM) and Data Rate Reduction (DRR) all allow reduction of the required C/N_o while maintaining the link performance in terms of BER. Whereas AC and AM allow the required energy-per-information bit (E_b/N_o) to be reduced, DRR aims to decrease the information data rate, at constant BER.

As already mentioned, making use of extra coding schemes or higher modulation levels implies longer bursts in the same frame for TDMA or larger bandwidth for FDMA, which penalises other users. Indeed, with these FMTs, a constant information data rate involves a higher transmitted data rate and requires the use of a larger part of the satellite resource. However, resource sharing can be improved by reducing the data rate, which translates into a further reduction of the required power. Indeed, it is possible to operate with constant resource by keeping the same transmitted data rate thanks to a decrease in information data rate. In this case, user data rates can be matched to propagation conditions: nominal data rates are used under clear sky conditions (no degradation of the service quality with respect to the system margin), whereas reductions of data rates are introduced according to fading levels.

A possible technique using this principle to counteract propagation fading has been designed in the framework of the OLYMPUS project. This FMT, based on the principle of Fade Spreading, has been tested within the DICE videoconference experiment [*Kerschat et al., 1993*]. This FMT consists of reducing the codec rate from 2.048 Mbit/s (nominal data rate) to 1024, 512 and 256 kbit/s when fading increases, which results in possible gains of 3, 6 and 9 dB. More precisely, the variable source data rate is combined with a pseudo-random data sequence at the fixed “clear sky” data rate. When fading appears, the source data rate is decreased while the PR sequence rate is kept constant, leading to a spreading of the data: the higher the spreading factor, the higher the processing gain.

The interest of the Fade Spreading method is to operate at constant satellite resource allocation per user (bandwidth, burst length) through constant transmitted data rate. The limitation of the method results in the possible compensation gain, a direct function of the range between nominal and smallest admissible information data rate for the user. Therefore, this FMT can be applied only for specific services which can tolerate a significant reduction of the information rate such as video transmission or data transmission (through an increase of transfer duration), but seems to be difficult to use with voice transmission for instance. Moreover, extra delay appears due to the necessary dialog between transmitter and receiver, as well as to the data rate reduction of the video signal.

Diversity techniques

The objective of these techniques is to adopt a network re-routing strategy in order to avoid impairments due to an atmospheric perturbation. Three types of diversity techniques can be designed: site, orbit and frequency diversity.

Site Diversity (SD)

Site Diversity can only be used for FSS (Fixed Satellite Services). This FMT has been used essentially in Ku-band, where the propagation conditions that could overcome the margin occur only during, relatively rare, strong events (convective precipitation, storms).

Heavy precipitation or a storm are very localised events, with a central convective cell of about 1 km diameter and surrounded by a wider area (several kilometres diameter) with exponentially decreasing rain rate. The principle of SD is to use the fact that two fades experienced by two Earth stations separated by a distance higher than the size of a convective rain cell (at least 10 km), are statistically independent [*Poiares-Baptista and Davies, 1994*]. The Earth station statistically affected by a weaker event is used and the information is routed to the original destination through a terrestrial network.

Typical diversity gains achievable with this method are between 10 dB and 30 dB at Ka-band according to the distance between Earth stations (from 5 km) [*ITU-R, 1994*]. The OPEX campaign has shown that the use of more than two stations does not improve the diversity gain. This method is particularly efficient (high diversity gain) when the percentage of time considered is low (high availability systems). Indeed, very low time percentages correspond to very strong and local events, like convective rains and storms. However, this technique requires the existence of terrestrial links between Earth stations. So actually, site diversity is suited to control stations and major gateways, but seems to be too expensive for low-cost VSATs or USATs without using public terrestrial networks.

Satellite diversity (SatD)

In relation to the current developments of new Ka-band satellite constellation systems, Satellite diversity (SatD) is one solution to prevent degradation of the service quality. SatD can be regarded in two different ways: on one hand, when designing the system, by optimising the size of the constellation (that is the number of satellites) in order to prevent communications at low elevation angles, and on the other in allowing Earth stations to choose between various satellites, the one which allows to establish the most favourable link with respect to the propagation conditions [*Capsoni and Matricciani, 1985*].

Some experiments have been carried out in the past, with SIRIO and OTS [*Capsoni et al., 1990*] and with OLYMPUS and ITALSAT [*Matricciani and Mauri, 1995*] spacecrafts. These campaigns have demonstrated the possible use of SatD as a FMT for future high-frequency satellite telecommunications systems. The SIRIO-OTS 12 GHz experiment has pointed out that the diversity gain (either statistical or instantaneous) is higher for low-elevation links than for higher elevation links [*Capsoni et al., 1990*]. These results have been obtained for the working frequency of 12 GHz and are expected to be improved in Ka-band.

As far as the OLYMPUS-ITALSAT SatD experiment is concerned, two kinds of conclusion have been drawn [*Matricciani and Mauri, 1995*]. For low attenuation ensure inhomogeneities in the meteorological cell). For high attenuation (convective clouds or precipitation), two situations may occur: either both attenuations are not correlated and therefore the diversity gain is high, or both attenuations are correlated and the efficiency of this technique is lower. In general, this SatD experiment has demonstrated that for this particular geometrical configuration (small angular separation between spacecraft placed on the GSO), the normalised gain, expressed in percent, is of the order of magnitude of the angular separation between satellites, expressed in degrees; this was 30 % in the case of the OLYMPUS-ITALSAT experiment. Furthermore, this result is reliable only for high percentages of time (>0.5%), because of the short duration of this experiment. Additional campaigns should allow to generalise these results.

For telecommunications systems based on a satellite constellation, SatD seems to be a valuable alternative or complement to site diversity. Although the maximum achievable diversity gain is higher in Site Diversity than in Satellite diversity (because in SD it is possible to have Earth stations far enough apart to experience non-correlated fade events which seems to be more difficult with SatD), SatD does not require terrestrial connections. However, from the operational point of view, using this FMT implies shifting the antenna pointing from one satellite to an other, which could lead to an interruption of service. This interruption can be brief if either ephemerides of both spacecraft have been introduced in the Earth station tracking software or if active antennas are used for the ground segment. A dual beam antenna could also be considered.

Frequency Diversity (FD)

Frequency Diversity is a technique which requires that payloads using two different frequency bands are available onboard [*Carassa and Tartara, 1988*]. When a fade occurs, the routing strategy adopts links using the lowest frequency band payload.

Currently, some new high frequency band systems should use on the one hand Ka or EHF bands and on the other hand X or Ku bands. For this kind of system, two frequency diversity techniques can be implemented, either cross-shaping or double-hop.

- Cross-shaping frequency diversity: the up-link and down-link frequency bands are not the same, and a switch onboard allows the transfer. To use it as a FMT to counteract propagation conditions requires that one or both users be equipped with two terminals (one in each frequency band).
- Double-hop frequency diversity: in order to counteract propagation conditions, the information has to be sent through a third user that is able to send the message to the original destination in the other frequency band.

This FD technique is relatively expensive, because it involves having one user with a pair of terminals, the first for the lower band and the second for the higher band. Furthermore, the sharing of the satellite resource is not optimised. In practice, this technique should be reserved for very specific communications.

Other FMTs

Other techniques, such as carrier reallocation [*Pujante and De Haro, 1998*], have been studied in the framework of COST 255, with the aim of improving the carrier to intermodulation ratio, a limiting impairment factor for a satellite link in multicarrier operation. With this technique, it is possible to avoid any modification of the transmission plan, that is the power and the centre

Eventually, Time diversity can be considered as a FMT that aims to re-send the information when the state of the propagation channel allows it to get through. However, this technique cannot really be considered as an adaptive FMT.

5.3.1.3 Operational considerations

In this paragraph, the field of application and the relative cost of each FMT will be assessed as a function of some characteristics of the communication system, such as: availability, type of coverage and meteorological characteristics of events.

FMTs planned in future systems

An overview has been compiled from some FCC filings and contacts established in the framework of COST 255.

Ka-band (30 GHz uplink - 20 GHz downlink) will actually represent the first frequency band in which FMT will be implemented with the objective of improving system availability. For first deployed version of Ka-band systems, it is likely that only basic FMTs will be developed, such as ULPC, DRR or diversity (see Table 5.3-1), more sophisticated techniques such as Adaptive Coding or Modulation only being implemented in a second step.

SatCom Syst.	Availability	FMT	Origin
Astra ARCS	≈ 99.5 %	UL Level Control - AC	COST 255
Astrolink	> 99.5 %	ULPC - DL AC	FCC sept. 95
Cyberstar	> 95 %	ULPC - AC - DRR - SD ?	FCC sept. 95
Dyanet-X	?	Cross-strap FD (C-Ku)	Ka-band'97
Euroskyway	99 to 99.9 %	Time Diversity - ULPC	Ka-band'96
Eutelsat-Ka	95 to 99.9 %	Nothing - ULPC	COST 255
Skybridge 2	> 98 %	ULPC	FCC dec. 97
Skystation	> 99.5 % (10^{-6})	?	Ka-band'97
Spaceway	> 99 to 99.5 %	ULPC - ?	FCC dec. 97
Teledesic	99 to 99.99 %	ULPC - SD	FCC july 95

Table 5.3-1: Ka-band filings

Furthermore, as the critical link for the propagation point of view will be the uplink (a 30 GHz fade is on average twice as high as a corresponding 20 GHz fade), these FMT should be implemented mainly on the uplink.

V-band (uplink around 48 GHz - downlink around 38 GHz) represents the next potential frequency band for multimedia systems. In this band, propagation impairments will be more severe than at Ka-band. Furthermore, due to the reduced difference between up and down link frequencies, it is no longer possible to consider that the uplink is more critical than the downlink. Then, unlike at Ka-band, it will be necessary at V band to implement FMT for downlinks (see Table 5.3-2).

SatCom Syst.	Availability	FMT	Origin
LM-MEO	> 97 % > 99.99 % with FMT	ULPC SD – SatD FD	FCC dec. 97
M-star	> 99 % > 99.99 TT&C	ULPC DLPC SD	FCC sept. 96
…			?

Table 5.3-2: V-band filings

Indeed, although the downlink frequency is lower than the uplink one, as the satellite technology at V band is less mature, the downlink could be the critical component of the link budget, (e.g. outbound links (links established from gateway stations to terminals) for mobile or VSAT systems with a double-hop two-way network topology) and will require specific attention to avoid a significant degradation of performance when faded.

Availability of FMT

The maturity of FMT could be evaluated when classifying these techniques in three categories (Table 5.3-3):

- in use today by operational planners,
- available in research institutes if required,
- research initiated but not mature.

In use today	**Available if required**	**Not mature - Research**
Simple Power Control	ULPC	Adaptive Modulation
Simple Extra Coding	DLPC	Beam Shaping
Frequency Diversity	Adaptive Coding	
Site Diversity	Satellite diversity	Joint FMT

Table 5.3-3: classification of FMT in terms of maturity

Up to now, mitigation techniques have been used mainly for systems operating at Ku-band (14 GHz uplink - 12 GHz downlink):

- Simple Power Control technique in FDMA systems, which consists in keeping a constant power level of all the carriers at the input of the transponder in order to prevent the capture effect or to limit intermodulation products. Furthermore, performed in real time, this control permits to compensate attenuation due to rain on the up-link.
- Simple Extra Coding technique: when a link is experiencing fading, introduction of coding allows to add redundant bits to the information, in order to detect and to correct errors caused by propagation impairments - which leads to a reduction of the required signal energy per information bit at constant BER.
- Frequency Diversity has been used for instance for satellites equipped with Ku- and C-band payloads; when a fade occurs, the routing strategy selects links using the lower frequency band payload.
- Site Diversity has been used when the propagation conditions that could overcome the margin occur only during strong events (convective precipitation, storms).

The last two techniques have already been implemented essentially for TT&C links, for which a

Some other techniques are ready to be used, such as Up-Link Power Control and Down-Link Power Control, Adaptive Coding and Data Rate Reduction, as well as Satellite Diversity for constellations. No significant difficulty is expected in the implementation of these techniques.

Three FMTs can rather be classified in the research domain:

- Adaptive modulation: the principle of this method is well known, but the problem lies in the practical implementation of modems and in the power available at the receiving level.
- On-Board Beam Shaping: this technique requires sophisticated active antennas and related processing to be placed on-board the satellite.
- Joint FMT, i. e. a combination of several single FMTs possibly represents the most promising solution.

Availability range objectives

Three types of FMT have been identified above: Power Control techniques (ULPC, DLPC and OBBS), Adaptive Signal Processing techniques (AC, AM and DRR) and diversity techniques (FD, SD and SatD). Due to their principles and to the consequences in terms of network resource sharing, each of these methods is adapted to a specific part of the availability range objectives of a satcom system.

Up-Link Power Control makes use only of transmitted Earth station power; therefore it can be implemented for any percentage of time, which makes this technique a very flexible one. The limitations of ULPC are the Earth station power range and the repeater gain margin for transparent repeaters, which means in practice that very strong fades cannot be compensated entirely with this technique. However the range of power control should be sufficient to counteract effects of clouds or weak precipitation (high percentages of time).

Regarding Down-link Power Control and On-Board Beam Shaping, the size of spot beams ($\theta_{3dB} < 0.5°$) in Ka and EHF bands will, in practice, allow to counteract events spread over an area of some hundreds of kilometres. The most efficient use of these techniques will be obtained if the aperture of spot beams does not greatly exceed the rain cell size. Consequently, DLPC and OBBS can be efficiently applied to large meteorological stratiform structures corresponding to high time percentages.

The advantage of Adaptive Signal Processing FMT is to be able to maintain the transmission data rate of the service, which makes also this technique a very flexible one. However, this kind of FMT is only interesting if the extra capacity does not represent a large part of the total satellite resource which would affect the overall performance of the system. For instance, without taking into account statistical fluctuations, if only 5 % of the links experience fading at any time, then the amount of common resource needed is only 5 % of the total required, if all Earth stations operate with a fixed margin [*Willis and Evans, 1988*]. Consequently, Adaptive Coding or Modulation techniques can only be really efficient if only a few Earth stations experience fading at the same time. Therefore, these techniques are best suited to local or to rare impairments (such as heavy clouds and strong precipitation) where the probability of simultaneous fading on many links is very low (decorrelated events). When fades are highly correlated, ASP is less effective [*Jones and Watson, 1993*].

The Frequency Diversity technique is relatively expensive, should be restricted to very specific communications and should be used to prevent a saturation of the system. From this assumption, it can be stated that Frequency Diversity can be applied to any percentages of time.

Geometrical Diversity techniques are more efficient if the atmosphere is not homogeneous, in order to be able to find another path not affected by a strong impairment (high diversity gain). This situation is more likely to be encountered when the percentage of time considered is very low

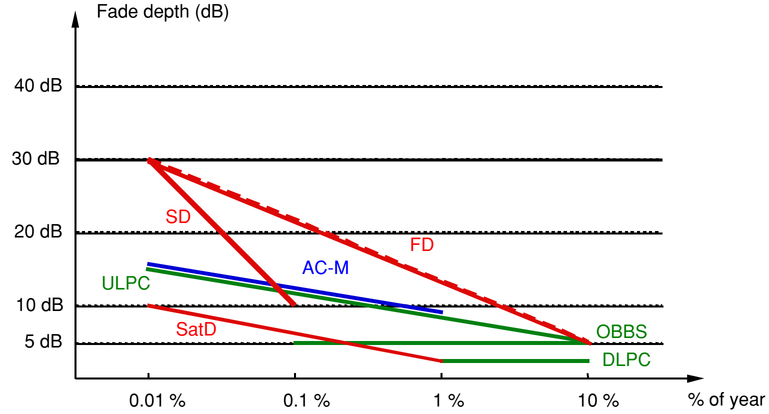

Figure 5.3-1: Example of FMT availability range at Ka-band

Figure 5.3-1 shows the availability range of different types of FMT considered in this study. This graph represents an example of the efficiencies that could be reached with these FMTs at Ka-band, with the following assumptions about the compensation range:

- ULPC: 5 dB (VSAT) to 15 dB (hubs),
- DLPC: 3 dB output power variation range for the satellite TWTA,
- OBBS: 5 dB gain range for satellite antennas,
- AC and AM: 10 to 15 dB E_b/N_0 range,
- SatD: 3 dB to 10 dB diversity gain,
- SD: 10 dB to 30 dB diversity gain in convective cells at Ka band,
- FD: up to 30 dB gain between Ku and Ka bands.

The relative efficiencies of these FMTs can be different depending on the frequency band considered. To compare these efficiencies more precisely it would be necessary to simulate overall link budgets, and to consider system architecture and access schemes.

Joint FMT

Since each FMT is adapted to a specific range of availability, these FMTs are quite complementary. Therefore, it is interesting to explore the possibility of implementing some of them simultaneously (joint techniques), on the one hand to improve the overall efficiency of the mitigation, on the other hand to extend the availability range of requirements [*Tartara, 1989*; *Acosta, 1997*].

For instance, Figure 5.3-2 shows the possible efficiency of a joint FMT constituted of ULPC, AC or AM, SatD and SD, with the assumptions of Figure 5.3-1, to cope with a wide availability range of requirements.

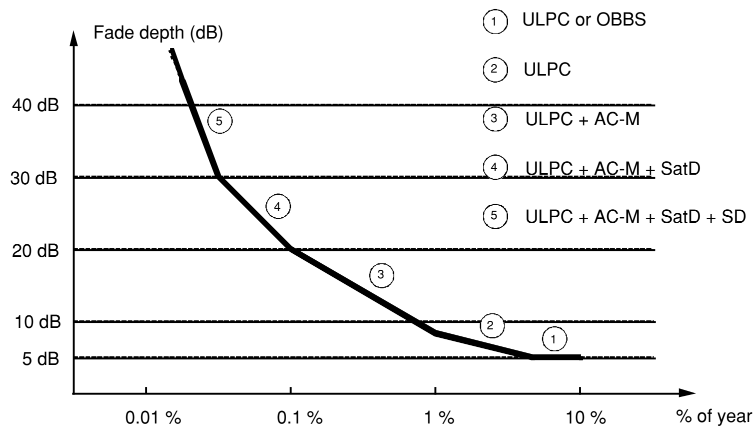

Figure 5.3-2: Example of joint FMT efficiency at Ka-band

In the framework of COST 235 [*COST 235, 1996*], a comparison was made between an ULPC with a 12 dB gain limit and an adaptive-TDMA point-to-multipoint system (Adaptive Signal Processing FMT) with a bandwidth expansion factor of 5, for terrestrial systems operating in the 20 GHz - 50 GHz band. This study showed that the performances of the two techniques are equivalent. However, it has also been demonstrated that a combination of the techniques allows a significant improvement to be achieved in terms of availability.

This conclusion of COST 235 can also be illustrated by a satellite experiment of a prototype Ka-band FMT, carried out with a TDMA station by the German and Swiss PTTs and DLR [*Schnell and Von Hugo, 1998*; *Kreuer et al., 1994*]. In this experiment, a joint FMT was implemented with ULPC and Adaptive Coding (punctured codes). It was demonstrated that ULPC alone allows to significantly improve system availability by compensation of fades up to 10 dB. For some strong events, Adaptive Coding has was able to increase availability a little more, a total fade of 18.5 dB having been compensated. However, attention has to be paid to time delay, the system having reacted too late in some cases of steep fade slopes.

The scheme relying on adaptive trellis coded modulation proposed by [*Gremont et al., 1999b*] for low rate SCPC VSAT return links offers a range of approximately 15 dB in steps of 1 to 2 dB, assuming uncoded 8PSK modulation for clear-sky i.e. no rain conditions. Such a fine quantization allows to operate closer to channel capacity.

5.3.1.4 Conclusion of the review

The objective of this section was to make an overview of the state-of-the-art in the field of Fade Mitigation Techniques to counteract impairments caused by tropospheric propagation to Earth-space telecommunications systems operating at Ku-band and above. Three types of FMT have been identified: Power Control, Signal Processing and Diversity techniques.

It has been demonstrated that some techniques, such as ULPC or DRR, are very flexible because they have an impact mainly on the terminal. Other techniques such as AC, AM or SD lead to a re-allocation of the system resources and therefore can not be applied without considering multiple access schemes and protocol issues.

In addition, the choice of which combination of FMTs to implement in a satcom system will strongly depend on the type of system. Indeed, some techniques such as ULPC should be relevant for systems in which high performance Earth station (hubs, gateways, trunking systems) can be designed. ASP techniques would be more suitable for VSAT systems in which solid state power amplifiers (SSPA) should be used at their maximum power (main part of the user terminal cost) in

This work points out two important aspects for new systems operating from Ku to V band:

- On the one hand, it appears that each FMT is adapted to a specific range of availability. Then these fade mitigation methods are quite complementary and can be implemented simultaneously (joint techniques) to extend the availability range of requirements. Following some conclusions of the COST 235 project and [*Vasseur et al., 1998*], this state-of-the-art report shows that Ka and EHF band satellite telecommunications systems with high service availability are technically possible only if a combination of different FMTs (Joint FMT) is implemented.
- On the other hand, such methods implemented individually can compensate only relatively small propagation impairments. It will be possible to improve the performance of the mitigation to a large extent, by carrying out a combination of different kinds of FMT when there is a need to transmit high priority information [*Vasseur et al., 1998*].

In Chapters 6.1 to 6.4, some FMTs are used in COST 255 test case analyses. These are listed in the following table:

	FMT actually simulated	**FMT forecast or possible**
Test case 1	ULPC + AM	AC
Test case 2	ULPC + DRR	AC - AM - DLPC
Test case 3	-	ARS - TD - SD
Test case 4	ULPC + DLPC	SD – Sat D

Table 5.3-4: FMT used in test case analyses

5.3.2 COST 255 developments

5.3.2.1 Simulation and performance evaluation of FMT Systems

At Ka or V band, the main limitations are due to the signal variations caused by clouds, rain attenuation, thermal noise and tropospheric scintillations. In order to build and test communication systems using FMTs, it is necessary to consider the modelling of the Ka-band faded satellite channel. Essentially this requires an extension of the link power budget analysis which can encompass the main statistical and dynamical characteristics of the atmospheric processes involved as well as system parameters.

Short-term analysis, relying on event-based simulation is useful for evaluating the real-time behaviour of an overall communication system in the presence of dynamic atmospheric fading. With such an approach, the focus is placed on optimising real-time algorithms (e.g. fade detection, prediction, data link layer ARQ protocols) so that satellite links can be serviced in a transparent and efficient manner. This can be done using propagation beacon data if available. An alternative is to synthesise time-series using DSP and use these generated signals [*Gremont and Filip, 1998*].

The ultimate objective is to design systems that can perform satisfactorily on a long-term basis. It is thus important to obtain estimates of the likely performance probably on a worst-month or yearly basis. This can be achieved either by running an event-based simulation over the required time span, or, in some simple cases using mathematical solutions. For example [*Gremont and Filip, 1999*] evaluated the expected CNR statistics for inbound and outbound channels of a duplex satellite link with ULPC with a 5 dB range. Once the CNR statistics are known it is quite straightforward to estimate the BER/throughput of practical communication systems.

FMT Techniques: Carrier Reallocation

Among satellite communications interference sources, intermodulation noise is the limiting impairment factor for a satellite link in multicarrier operation. The higher the operating point (lower point, $C/I_{intermodulation}$<C/N and << C/I on the uplink). So, in rain fade conditions, the improvement of the $C/I_{intermodulation}$ ratio of the affected carrier is a useful technique to improve the quality of service.

The proposed approach [*Pujante and De Haro, 1998*] is to apply the simulated annealing optimisation technique on a dynamic basis to those carriers affected by rain fade in a multicarrier satellite transponder. The advantage of this proposal is that it avoids any modification of the transmission plan, that is, the power and the centre frequency of all carriers remain unchanged, except for the faded carrier, which is reallocated to a frequency where the best $C/I_{intermodulation}$ ratio can be found. This technique can be implemented either on a single station, or by means of a NMS (Network Management Station) on a VSAT network.

As a first advantage, the optimised configuration for the transmission plan is more robust in case of a rain fade, than a classical transmission plan approach with correlative frequency assignment.

As this optimisation technique can be reiterated over any configuration, after the modification of any of the carrier blocks in the transponder, it can be used to redistribute the intermodulation noise of any carrier block in the transponder under rain fade conditions. Thereby all carriers contribute to the protection of the faded carrier, but without modification of the transmission plan of the carriers that keep operating under nominal conditions, and only the faded carried should re-optimise its central frequency.

In the studies developed, this improvement is as high as 4.4 dB with respect to the classical transmission plan approach, and 0.7 dB with respect to the previously optimised configuration. In digital transmission this margin is enough to bring the signal back above the demodulator threshold.

The implementation of this technique is feasible on a station by station basis (point-to-point links) or on a NMS station attended-VSAT network basis. The best operational advantage arises from the fact that there is no need to modify the transmission plan for the carriers that are not affected by rain fading.

5.3.2.2 Problem of impairment detection

Up to now, the use of Fade Mitigation Techniques has been discussed from the system point of view. In implementing an FMT, a real problem is to detect and predict, in real time, the dynamic behaviour of a propagation impairment. It is then necessary to discuss the methods for detecting and quantifying a possible fade, and the method of distributing the information to the equipment that is going to implement the compensation (transmitting Earth station, satellite, control station…).

Possible configurations

From the operational point-of-view, the first action to perform consists of evaluating when an outage of the system due to propagation conditions is going to happen. More precisely, it implies being able to detect a propagation event and to quantify it in order to estimate whether or not the system margin is going to be exceeded. Therefore, as it is necessary to measure the depth of an event, this measurement must be done on the particular link which suffers it, the ground segment (either the transmitting or the receiving Earth station) being the most suitable to carry out this function, for technical (identification of the station suffering the fade) and cost reasons.

From this assumption, three kinds of detection concepts can be designed for an Earth station [*Egami, 1982*; *Hörle, 1988*; *Cacopardi et al., 1993*; *Dissanayake, 1997*]: open-loop, closed-loop and hybrid-loop.

Open loop principle

The open-loop detection concept relies on the estimation, by the Earth station, of the uplink impairment, from a measurement of the propagation conditions. This measurement can be carried out in four different ways:

- temperature, pressure, humidity and rain intensity measurements realised with a meteorological station (with a rain-gauge),
- sky brightness temperatures measured with a multifrequency radiometer,
- attenuation measurements realised from a satellite beacon operating at uplink frequency,
- attenuation measurements realised from a satellite beacon operating at downlink frequency.

Meteorological and radiometrical detection concepts seem difficult to implement for systems with low cost constraints on the ground segment. Regarding rain-gauge measurements, the accuracy that could be reached is not very good, because it does not allow to know the distribution of the rain intensity along the whole path, but only at the rain-gauge location.

Accordingly, an analysis performed for the ACTS campaign (USA) [*Dissanayake, 1997*] has shown that a sufficient accuracy can only be obtained with beacon measurements. Of course the best accuracy can be obtained with satellite beacons operating at both uplink and downlink frequencies (in this case, there is no frequency scaling to perform). The World Administrative Radio Conference held in 1992 allocated a frequency band for uplink frequency beacons at Ka-Band.

However, it seems that the implementation of an uplink frequency beacon receiver in the Earth stations (especially VSATs) will be considered too expensive for new satellite systems operating at Ka or EHF bands, whereas it is not the case for a downlink frequency beacon (already in the channel receiver frequency band).

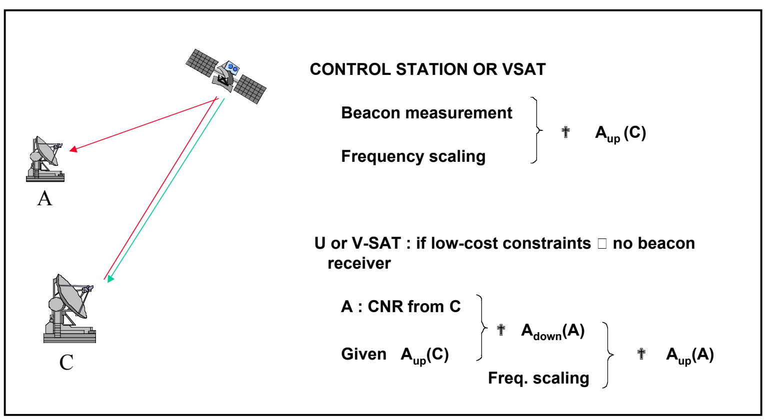

Figure 5.3-3: Basic open-loop principle

In practice, the open-loop detection scheme will be based on the measurement of a downlink beacon (in general the satellite TT&R beacon) preferably in the downlink frequency band (see Figure 5.3-3). Once the downlink attenuated signal has been measured, the use of instantaneous frequency scaling algorithms between uplink and downlink frequencies allows to estimate the uplink fade in real-time (for the downlink, the impairment is directly measured by the Earth station). Differently from both following concepts, the open loop method presents the advantage of not implying the

Closed loop principle

In the closed-loop detection concept, the estimation by the Earth station of the uplink impairment is made from the measurement of the overall link performance.

The method is based on an iterative process. In a first step, Bit Error Rate or Carrier-to-Noise Ratio estimations are performed by the Earth station. The result of this measurement is afterwards compared to a threshold, which represents the required performance for the link to be operational. When this threshold is crossed, a FMT procedure is initiated.

With this concept, it is necessary to distinguish between the impairments on the uplink and the downlink, which again leads to processing instantaneous frequency scaling algorithms.

Hybrid loop principle

The objective of the hybrid-loop detection concept is to use two different measurements in order to avoid the use of frequency scaling algorithms (see Figure 5.3-4).

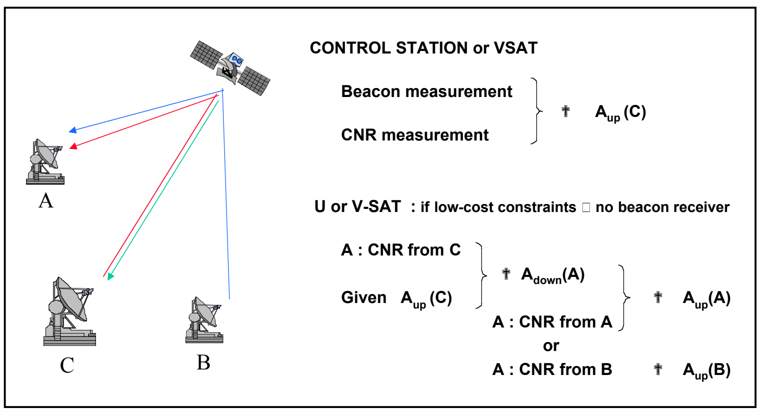

Figure 5.3-4: Basic hybrid-loop principle

In the case of a conventional Earth station (control station, gateway), overall link performance and downlink frequency beacon measurements are performed at the same time. The uplink fade is determined from the difference between these measurements.

In the case of a VSAT (or a USAT) terminal, beacon measurements at a frequency different from the communication links cannot be performed, due to cost considerations. Therefore, a reference signal from a control station (which knows its uplink fade by use of the previous method) can be used in place of the beacon signal. The downlink impairment is then deduced by the VSAT from the measurement of the reference link and from the knowledge of the Control station uplink fade transmitted through the reference signal. The corresponding VSAT uplink impairment is therefore calculated by subtraction of this reference downlink fade, from its own back to back overall signal measurement.

If no link is available from a control station, the signal of another VSAT, itself connected to a control station, can be used. Both cases lead to an increase in time delay, which can degrade the efficiency of the mitigation.

[*Filin, 1996*] describes an OSI data link protocol whereby the imbedded FMT (adaptive main advantage of such an approach is that fade detection and the required communication of FMT specific information between transmitter and receiver are inherently provided by an appropriate extension of the standard OSI Layer 2 protocol. In such a case, there is no need to discriminate between up and down link fades, which may improve upon the overall accuracy since there is no need for instantaneous frequency scaling. This technique bases its decision and actions on the actual quality of the received data. It can thus be considered as objective since it does not rely on some open loop parameters of the physical channel.

Comparative evaluation

The objective of this paragraph is to compare the relative performances of these three detection concepts. Therefore, some steps that are involved in each scheme, such as scintillation filtering or determination of clear sky attenuation (see Chapter 2.1), will not be developed here.

Open-loop detection scheme

The relative efficiency of the open-loop detection scheme depends on the accuracy of both beacon measurements and frequency scaling.

Beacon measurements are affected by instrumental drifts such as: instabilities of the Earth station radio-frequency chain, variations of the satellite EIRP (transmitted power, pointing accuracy, platform instabilities), and thermal noise. With a good calibration device, a relative accuracy of ±1 dB can be obtained [*Castanet et al., 1997*], which should be adequate for FMT [*Willis and Evans, 1988*].

As far as frequency scaling is concerned, several factors have to be processed, corresponding respectively to gas, cloud and rain attenuations, and also to scintillation and depolarisation [*Sweeney et al., 1992*; *Rucker, 1994*; *Salonen et al. 1994*; *ITU-R, 1994*; *Mauri et al. 1996*]. Experiments realized in the framework of the ACTS campaign (USA) have demonstrated that an accuracy better than ±2.5 dB can be obtained in processing only rain attenuation and clear sky scintillation fixed frequency scaling ratios [*Dissanayake, 1996*]. At Ku band (INTELSAT VI experiment), an accuracy better than ±1.5 dB has been obtained by same authors [*Dissanayake et al., 1993*].

At Ka band, the indirect estimation of the down link attenuation has to be scaled according to the ratio of the frequencies, by a factor of approximately $(f_2/f_1)^{1.72}$. Consideration must be given to the uncertainty of the instantaneous ratio between the two attenuations (particularly important for 20/30 GHz), which can be rather dispersed, especially in the case when rain is not the only cause of fading.

The ratio between rain attenuations has been studied during [*COST 205, 1985*]; it was found that for outage probabilities lower than say 0.1% (rain effect prevailing), this ratio, *r*, can be considered a log-normal variate whose standard deviation $\sigma_{\ln r}$ is 0.13 and whose median is given by the almost constant ratio between the equiprobable attenuation values (approximately $r_{50\%} = (f_2/f_1)^{1.72}$; $<\ln r \geq 1.72.\ \ln(f_2/f_1)$).

This has been confirmed by OLYMPUS [*Poiares-Baptista and Davies, 1994*] and ITALSAT measurements.

Closed-loop detection scheme

The relative efficiency of the closed-loop detection scheme depends on both overall link

It is interesting to consider the type of measurement to realise. Two kinds of measurements are theoretically possible: Carrier-to-Noise Ratio or Bit Error Rate measurements performed by the Earth station. In the case of BER estimations, it is necessary to have a sufficient number of errors to obtain an accurate BER and therefore to be able to conclude about the fade level. Consequently, extra time delays, which increase with decreasing data rate, have to be taken into account before the implementation of the mitigation. The following points must be considered:

- While propagation conditions are in the range of the system margin, BER will be too small (typically about 10^{-7} - 10^{-9}) to allow accurate BER measurements in real-time. In this case, Carrier-to-Noise Ratio seems more suitable for fade detection.
- When propagation conditions are leading to the crossing of the system margin, BER is increasing extremely quickly. In this case, there will not be enough time to adjust the mitigation. Full capacity will then likely be used.

Therefore, even if Carrier-to-Noise Ratio does not allow to carry out measurements with high accuracy, it seems to be more suitable for propagation impairment detection. However, when concatenated codes are implemented, reliable BER measurements can be made at the output of the inner decoder.

Secondly, reliable propagation measurements are difficult to achieve from the signal transmitted by the satellite repeater. Instrumental drifts include, as in the beacon case: contribution of thermal noise, instabilities of the Earth station radio-frequency chain, variations of the satellite EIRP due to pointing errors of the satellite receiving antenna and especially the instantaneous repeater gain which is not known with a good accuracy (≈ 3 dB uncertainty). Moreover, the dynamic range of the measurement (with respect to the beacon one) is lower, because the measurement includes both uplink and downlink attenuations.

In addition it is necessary to discriminate up and downlink contributions to propagation impairments, which implies the use of instantaneous frequency scaling algorithms as in the open-loop scheme. Another approach has been proposed [*Willis and Evans, 1988*]: to monitor many carriers from different Earth stations. As only a small proportion of the carriers is likely to be attenuated at the same time, the knowledge of the number of faded carriers makes it possible to deduce whether the propagation impairment affecting the useful carrier is on the up or the downlink (a relatively homogeneous attenuation of all carriers suggesting a downlink impairment).

In conclusion, measurements of overall link performances are not really accurate with respect to beacon measurements. Such measurements have been carried out in the past, in particular with the OTS satellite and were abandoned for this reason.

Hybrid detection scheme

A hybrid detection scheme is characterised by the best performances in term of accuracy, since it uses beacon measurements without using frequency scaling algorithms.

In fact, the limitation of this concept is firstly linked to the delay involved in carrying out the measurement before the introduction of the mitigation. This extra-delay, which represents half a hop (station to satellite) in the case of a control station, increases to a hop and a half in the case of a VSAT. For a geostationary satellite, this extra time delay ranges from 125 ms for a control station to 375 ms for a VSAT terminal.

Secondly, as two signals have to be processed, the processing delay is double. In fact, it time necessary to filter scintillation in real time is about 10 s, as the mean fade slope during an event is about 0.2 dB/s at Ka-band (0.1 dB/s at Ku-band), the total extra-delay introduced can cause an error of ±2 dB at Ka-band (±1 dB at Ku-band) [*Poiares-Baptista and Davies, 1994*; *Ortgies, 1996*].

Comparative analysis

The comparison between the detection concepts defined above is made mainly between open-loop and hybrid-loop schemes.

The interest of a basic closed-loop scheme is to avoid the implementation of a specific beacon receiver that would increase the cost of VSAT terminals. However, this detection concept is not very attractive, since it keeps the drawback of open-loop (frequency scaling) without the advantages (simplicity, accuracy of measurements). In fact, the feasibility of FMT based on this control scheme seems to be doubtful.

The advantages of the open-loop detection scheme are a good accuracy and a good dynamic range for the beacon measurements. This concept is quite simple and low-cost. In addition, differently from both of the following concepts, the open-loop method offerss the advantage of not implying an extra allocation of system resources. The effectiveness is actually only conditioned by the knowledge of the instantaneous frequency scaling ratio which varies in a significant way during convective events. However, experiments carried out in the USA [*Dissanayake et al., 1993*; *Dissanayake, 1997*] have demonstrated that accuracies of ±1.5 dB at Ku-band and ±2.5 dB at Ka-band can be achieved with fixed frequency scaling ratios.

As far as the hybrid-loop detection scheme is concerned, the accuracy of the method itself is better than in closed-loop because it is not necessary to use frequency scaling. The improved accuracy is balanced by a more complex system architecture and therefore by an increase in cost. In addition, this concept is characterised by extra time delay, which induces a new error contribution, which can be of the same order as open-loop accuracy for small low-cost terminals.

The different error contributions for a system operating at Ka-band are summarised in Table 5.3-5, these contributions being summed in a quadratic way:

Error contribution	Open-loop	Closed-loop	Hybrid-loop
Measurement accuracy	± 1 dB	± 3 dB	± 1 dB
Frequency scaling	± 2.5 dB	± 2.5 dB	/
Processing time delay	± 2 dB	± 2 dB	± 2 dB
Extra time delay	/	/	± 2 dB
Total error budget	± 3.4 dB	± 4.4 dB	< ± 3 dB

Table 5.3-5: Example of error budget at Ka-band

It appears that the interest of open-loop or hybrid-loop schemes depends on the system architecture and on the frequency band. Indeed, according to the relative difference between uplink and downlink frequencies, the accuracy of frequency scaling algorithms may or may not be acceptable.

Table 5.3-6 gives the results of the technical analysis in relation to frequency band (without considerations of cost), the analysis being essentially conditioned by frequency scaling accuracy.

Frequency Bands	Ku FSS	Ku BSS	Ka	V	EHF
uplink frequency	14 GHz	18 GHz	31 GHz	< 50 GHz	44 GHz
downlink frequency	12 GHz	12 GHz	21 GHz	> 40 GHz	21 GHz
$\Delta F / F_{down}$	17 %	50 %	48 %	< 25 %	110 %
appropriated mode	open loop	open loop or hybrid loop	open loop or hybrid loop	open loop	hybrid loop

Table 5.3-6: Suitability according to frequency band

For instance, at Ku-band the accuracy of frequency scaling is quite good, therefore it does not seem useful to implement a hybrid-loop detection scheme which is more complicated and expensive than an open-loop scheme. On the contrary, at EHF band, uplink and downlink frequencies are relatively far apart, which leads to the preference for the hybrid-loop concept.

5.3.2.3 Predictive control

All the detection concepts defined in previous paragraphs can be considered as *a posteriori* techniques, since the system is able to react only after detection of an event. Therefore, extra time delay is introduced when processing detection of an event and estimation of the mitigation to be carried out, which implies a delay in the activation of the FMT.

This extra time delay leads to other error contributions that could be reduced through the implementation of real-time predictions at the terminal level. Actually, two kinds of prediction can be realised in real time: instantaneous frequency scaling ratio and channel behaviour predictions.

Instantaneous frequency scaling ratio

As already mentioned, the frequency scaling ratio can exhibit a strong variation during an event, specially for convective rain. This behaviour is characterised by a hysteresis effect [*Sweeney et al., 1992*], mainly caused by dynamic variations of drop size distribution, effective path length through the precipitation and antenna effects [*Dintelmann et al., 1993*].

Results from [*Rucker, 1994*] obtained during the OPEX campaign have shown that errors due to the use of a fixed frequency scaling ratio can reach up to ±4 dB [*Ortgies, 1993*]. An improvement can be made to the method, either by the introduction of a variable frequency scaling ratio [*ITU-R, 1994*], or by the modelling of the inhomogeneity of the medium from differential attenuation and phase measurements [*Ortgies, 1993*].

[*Gremont and Filip, 1998*] proposed an open-loop statistical model for the instantaneous frequency scaling of rain attenuation. This model considers the impact of random variations in rain drop size distribution on the scaling factor. The model is further developed for inclusion in fade prediction schemes required in FMTs.

Instantaneous frequency scaling procedures recommended in [*ITU-R, 1994*] only take into account rain attenuation. In reality, other effects, such as gaseous, cloud and melting layer attenuation as well as scintillation (in both clear sky and clouds) and depolarisation (due to rain and ice), must be considered. Some procedures have been proposed to calculate frequency scaling ratios due to gas and clouds [*Salonen et al., 1994*], scintillation [*Ortgies and Rucker, 1992*] and depolarisation [*Mauri et al., 1996*].

It may also prove important to consider the impact of the variability of the scaling factor of scintillation variance. To date the ITU-R only proposes a fixed value for this scaling factor. However, there is experimental evidence that the ratio is highly random. Such models can naturally be included in advanced detection schemes relying on a variable detection margin [*Gremont et al., 1999b*].

Short term prediction of the channel behaviour

Such methods aim to estimate the channel behaviour in real-time, so that the system can react at the moment where the event is occuring, rather than afterwards. In other words, it aims to determine attenuation at time t + Δt, from the attenuation at time t. To reach this objective, real-time predictions of fade slope have to be carried out [*Gallois, 1993*; *Willis and Evans, 1988*].

In the frame of the OPEX campaign [*Poiares-Baptista and Davies, 1994*], the feasibility of short-term prediction of the propagation channel behaviour, and the interest of introducing fade slope data were demonstrated. An autocorrelation analysis was carried out on a 30 GHz OLYMPUS event, and showed that attenuation correlation time was more than 100 seconds, whereas that for scintillation was less than 2 seconds, for the same event. In addition, it was demonstrated that the introduction of fade slope data could improve the prediction, although the improvement was not relevant for this particular event. In Chapter 6.2, a practical application is given of the use of the fade slope information to predict in real time the behaviour of the propagation channel for a Ka-band videoconference VSAT system [*Vasseur et al., 1998*].

An advanced short-term predictor using a self-tuning minimum-variance algorithm has been applied successfully to Olympus Ka band data. This was then used for the estimation of the performance of adaptive coding and adaptive symbol rate FMTs [*Gremont et al., 1996, 1997*]. The self-tuning predictor has been characterised on a long-term basis and a statistical model has been developed to estimate the impact of fade detection/prediction on the overall performance of practical FMT systems. The self-tuning predictor has also been compared to more classical schemes such as the slope-based predictor and the self-tuning predictor was found superior [*Gremont, 1997*]. Due to its self-tuning property the predictor will track naturally the changes in fade dynamics due to the non-stationarity of the rain process. Finally, since it is based on a minimum variance criterion, it can also be used to separate rain/cloud attenuation from amplitude scintillations in a quasi optimum way. This is particularly useful if instantaneous frequency scaling of each fading component is needed.

Management of FCM resources can also be made using Neural Networks. [*Mayligin et al., 1996*] describe a generic FMT controller which relies on an artificial neural network. Here the fade prediction and the countermeasure decision are merged into a single subsystem which can drive the embedded FMT directly. A first stage estimates mean attenuation and scintillation standard deviation. Decision thresholds are then implemented and give as an output the required FMT setting for the detected/predicted propagation conditions.

5.3.3 Conclusion

This chapter has presented the work carried out and the results obtained in the framework of the "System and simulation issue" Working Group of COST 255.

In the first part, an overview has been presented of the state-of-the-art in the field of FMT to counteract impairments caused by tropospheric propagation to Ka-band and EHF Earth-space telecommunications systems . Three types of FMT have been identified: Power Control, Signal Processing and Diversity techniques.

It has been demonstrated that some techniques, such as ULPC or DRR, are very flexible because they mainly have an impact only on the terminal. Other techniques, such as AC, AM or SD, lead to a re-allocation of the system resources and therefore cannot be applied without considering multiple access schemes and protocol issues.

In addition, the choice of a combination of FMTs to implement in a satcom system will depend systems in which high performance Earth stations (hubs, gateways, trunking systems) are involved. ASP techniques would be more suitable for VSAT systems in which SSPAs should be used at their maximum power (main part of the user terminal cost) in order to offer the highest possible data rate to the user.

This work points out two important aspects for new systems operating from Ku to V bands:

- On the one hand, it appears that each FMT is adapted to a specific range of availability. This means that these fade mitigation methods are quite complementary and can be implemented simultaneously (combined techniques) to extend the availability range of requirements. Following some conclusions of the COST 235 project and [*Vasseur et al., 1998*], this report shows that Ka and EHF band satellite telecommunications systems with high service availability are technically possible only if a combination of different s (Mixed FMTs) is implemented.
- On the other hand, each method implemented individually can compensate only relatively small propagation impairments. It will be possible to selectively improve the performance of the mitigation to a large extent, by carrying out a combination of different kinds of FMT when there is a need to transmit a high priority type of information [*Vasseur et al., 1998*].

In a second section, developments carried out in the framework of COST 255 in the field of FMT have been synthesised.

However, FMT cannot be applied without a knowledge of real-time propagation conditions from fade detection. Accurate instantaneous estimation of fade dynamics (fade and interfade duration, fade slope, fade depth…) is required, with only a short time delay before the introduction of the compensation.

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5.3.5 List of acronyms

AC	Adaptive Coding
AFS	Attenuation due to Free Space
AGC	Automatic Gain Control
AM	Adaptive Modulation
AP	Attenuation due to tropospheric Propagation
ARS	Adaptive Resource Sharing
ASP	Adaptive Signal Processing
B	receiver noise Bandwidth
BSS	Broadcasting Satellite Service
C/N	Carrier-to-Noise Ratio
CS	Cross Shaping
DH	Double Hop
DL	Down-Link
DLPC	Down-Link Power Control
DRR	Data Rate Reduction
EIRP	Equivalent Isotropic Radiated Power
ES	Earth Station
FD	Frequency Diversity
FMT	Fade Mitigation Technique
FS	Fade Spreading
FSS	Fixed Satellite Service
G/T	figure of merit
IBO	Input Back-Off
k	Boltzmann's constant
MSS	Mobile Satellite Service
OBBS	On-Board Beam Shaping
OBEC	On-Board EIRP Control
OBO	Output Back-Off
OBP	On-Board Processing
PC	Power Control
SatD	Satellite diversity
SD	Site Diversity
SEC	Simple Extra Coding
SL	SateLlite

SSPA	Solid state power amplifier
TCM	Trellis Coded Modulation
TT&R	Telemetry, Telecommand and Ranging
TWTA	Travelling Wave Tube Amplifier
UL	Up-Link
ULPC	Up-Link Power Control
USAT	Ultra Small Aperture Terminal
VSAT	Very Small Aperture Terminal